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Final Report

OIL-POLLUTION DETECTION AND MONITORING FROM SPACE USING ERTS-1

GARY C. GOLDMAN
ROBERT HORVATH
Infrared and Optics Division

JULY 1975

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FORMERLY WILLOW RUN LABORATORIES. THE UNIVERSITY OF MICHIGAN
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16. Abstract

The purpose of this report is to demonstrate the feasibility of using satellite data as a means of monitoring and detecting oil spills on oceanic and estuarian waters.

Three reported spills were investigated using four digital-computer, compatible techniques on ERTS-1 data. A spill on the Atlantic Ocean (off Virginia) was studied to develop spectral signatures (Chapter 3). Another spill, in Oakland Bay, was studied by ratioing spectral channels (to try to eliminate turbidity effects) and by summing different spectral channels to look for anomolus values caused by oil (Chapter 4). The final spill, off Southern California, was investigated by looking for anomolus values in each channel separately (Chapter 5).

The results of this study (Chapter 6) indicate that any of these methods might be usable if the spill is large enough to be seen by satellite, if the spill occurs more than a few kilometers off shore, and if the sky and water are relatively clear. In the case of the Atlantic spill, identification of material was not possible; and in the other two cases, the spills could not be detected at all.

ERTS-1 was not condidered feasible for this type of work (Chapter 7) because of its 18-day overpass frequency, the few spectral channels, the extended bandwidths,

(Abstract continued)

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PREFACE

The necessity of detecting and monitoring an increasing number of coastal oil spills has precipitated an increase in the evaluation of various surveillance methods.

The purpose of this study is to evaluate satellite-surveillance methods, specifically ERTS-1, as a means of detecting and monitoring oil spills.

Various digital-computer, compatible methods were attempted in order to develop, or at least evaluate, the best means of analyzing the data.

The work was done under contract NAS5-21783 for the National Aeronautics and Space Administration. I would like to thank project montior, Edmund F. Szajna, for his assistance in this state-of-the-art study.

Those people included in making this work successful were Drew Urbassik, Diana Rebel, and Dr. Chester Wezernak, all of whom were of great technological and moral assistance.

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SUMMARY

The purpose of this study was to evaluate the feasibility of using satellite information, specifically ERTS-1, as a means of detecting and monitoring oil spills.

Various digital-computer techniques were used on three different oil spill locations, one in the Atlantic Ocean (off Virginia), one in Oakland Bay, and one off Southern California.

The conclusions of the study are as follows:

(1) Oil spills may be detected from space provided the following conditions exist: clear sky over the slick, relatively clear water, a spill more than a few kilometers from land, and a spill at least hundreds of meters long

(2) Near-shore, coastal, bay, harbor, or river spills are very difficult to identify - but they might possibly be detected

(3) Positive indentification of the nature of the spill is very improbable using ERTS-1 spectral channels

(4) A satellite surveillance and monitoring system must have daily visibility, high resolution, and many, narrow spectral channels to be successful in identification and detection of oil spills.

OIL-POLLUTION DETECTION AND MONITORING FROM SPACE USING ERTS-1

1
INTRODUCTION AND SUMMARY

Petroleum products are becoming more commonly encountered as pollutants of our coastal and inland waters. These products result from natural seepage from the earth, accidental loss from equipment that is processing or using oil, deliberate dumping of oil waste from ships and coastal processing plants, or—even more frequently in recent times—from collision of oil tankers. A timely detection method is necessary to enforce regulatory laws regarding oceanic dumping, to detect unreported spills so that financial liability can be assigned, and to prevent ecological, aesthetic, or financial damage and loss.

Improvements in aerial and satellite instrumentation and data-processing techniques now provide another means of monitoring and detecting oil over large areas of water. Specifically, advances made in multispectral sensing by remote means have increased the possibility for detection and identification of oil spills. With the presence of the ERTS-1 satellite, periodic scanning areas of coastal waters, as well as observation and monitoring, now may be accomplished using both satellite and conventional methods.

The purpose of this study is to use ERTS-1 data to confirm, or at least investigate, the possibility of monitoring and detecting oil spills from space. An attempt is also made to define oil-slick signatures from such a platform. Another purpose is to evaluate the usage of the ERTS-1 sensor system for oil-pollution detection and monitoring. The final purpose involves evaluating the utility of any space system for such a use.

During the course of this study, three suspected oil spills were investigated. These three spills represent different conditions under which floating oil might be seen. One spill, off the southern coast of California, was the result of a collision of two vessels. The processing of data from this spill was difficult since the spill broke up into small segments which were indiscernible from the background water conditions. The second spill, the result of the dumping of waste oil, occurred on the inner harbor of Oakland Bay. The processing techniques involved for this case were hampered by the nearness of the adjacent land and by the highly turbid water in the bay. The third investigated area was in the Atlantic Ocean off the Virginia coast. This case was one in which the imagery from the satellite was the only source of information about the slick. Processing this event was easier than the other two, as this spill was not near land and was located in relatively clear water. For this case, various techniques were tried to verify the occurrence of the slick, identify it, and assign it spectral signatures. In summary, we could not say we detected oil (or in fact anything) in the Pacific and Oakland Bay cases; and although we made a positive detection, identification was not confirmed for the Atlantic case.

The last portion of this study is devoted to the evaluation of the ERTS-1 program and its potential use as a satellite monitoring and detection system for oil slicks. Evaluation is made as to the frequency of overflights, the acceptability of the detectors and their given channel bandwidths, and the usability of the data, considering its clarity and background noise.

2
THEORY

This chapter is devoted to a brief description of optical properties of oil and water as seen from space, ERTS-1 instrumentation, some general radiation (visible and infrared) detector difficulties, and the constraints on using ERTS-1 as a detector and monitor of oil spills.

2.1 OPTICAL PROPERTIES OF OIL ON WATER

The optical properties of oil, water, and the oil-water interface of most interest to this study are specular reflectance, diffuse reflectance, extinction coefficient, index of refraction, and scattering coefficient. These properties are discussed in References 1, 2, 3, 4, and 5.

A summary of all the effects of the total reflectance of water, and oil on water, is that the specularly reflected component of the radiance from the oil slick will always be larger than that from water of similar surface roughness. This will exist regardless of sea state or illumination level (except in the case of whitecaps). However, the slick may sufficiently reduce the capillary waves present so that the otherwise-present glitter pattern is subdued within the slick boundaries. In the case of diffuse reflectance (at least in the spectral region of our concern), the diffuse reflectance of natural water exceeds that of oil slicks. The slick tends to reduce the effective diffuse reflectance both by absorbing the downwelling energy (from the sky and sun) before it reaches the water and by absorbing the upwelling energy after it leaves the water. Thus, the diffuse reflectance of a thicker oil slick on water will be less than that of a thinner one. The relative magnitude of the two components of reflectance (diffuse and specular) from a target is, therefore, a function of the oil thickness, the solar-zenith angle (the angle above the horizon), the total solar illumination, the sea state, and the type of oil. It is impossible, therefore, to predict the relative target reflectance of an oil slick on water as being more or less bright in appearance than water alone.

An example of this inability to predict relative total reflectance is seen next. The thickest portion of the oil slick may be located at or near the center of the slick (which often occurs). This center core may be darker (lower reflectance) than the surrounding water, if it is thick enough to seriously inhibit the diffuse upwelling radiation from the water. The

upwelling may be the major component of the reflected energy in turbid water. Or, the core may be brighter than the surrounding water, if the water is relatively clear and specular reflectance is dominant—oil always has a higher specular reflectance than water. It is this apparent paradox that makes identification of oil spills difficult without adequate ground data to support the remote sensing.

To this inconclusiveness as to the brightness of the center portion of the oil relative to the surrounding water, we must add the following complicating conditions. Natural water, sea or fresh, has extremely low reflectivity, about 2-10%. This results in extremely low-magnitude signals from the sensors on the satellite detectors. In some cases, in fact, the random electronic noise may generate signals higher in magnitude than those of the water or the oil. Therefore, it is sometimes necessary to measure variations of the very small target signal superimposed on a larger fluctuating noise signal. This produces ambiguous results.

Another difficulty in assessing the characteristics (or even achieving positive identification) of oil floating on water is the possible presence of suspended particulate matter or of plankton (chlorophyll) in the water. This will increase the reflectivity of the water (diffuse component) and overshadow the presence of oil. Correcting for this effect may include looking at the output signal from different spectral channels at the same time. Some channels are very sensitive to plankton, some are sensitive to suspended particulate matter. But in almost all cases of all channels for moderate-thickness films, the reflectivity of oil on water should be uniformly higher than that of water alone. Techniques of ratioing total radiance values from one channel to another can help separate these effects and may confirm (or at least strongly suggest) the presence or absence of oil. In one of the cases discussed in this report (Oakland Bay, Section 4), this ratioing technique was used.

2.2 ERTS-1 INSTRUMENTATION

The purpose of this brief description of the satellite instrumentation is to give the reader some background to the more thorough description of some of the procedures, difficulties, and solutions discussed later.

We are concerned here with the multispectral scanner (MSS) on ERTS-1. This instrument has the capability of simultaneously looking at a single portion of the earth with four separate radiation-receiving detectors. Each of these detectors is sensitive (after applying appropriate optics and filtration) to a particular wavelength region of the electromagnetic radiation spectrum. The channels, or spectral regions, are designated by the names MSS-4, 5, 6, and 7. The wavelength regions and sensitivities (output for a given observed radiance) for these channels are shown in Table 1.

TABLE 1. ERTS-1 MULTISPECTRAL-SCANNER CHANNELS

MSS Channel	Spectral Limits (μm)	Radiance/Count ($mW/cm^2\ sr$)
4	0.5-0.6	0.0195
5	0.6-0.7	0.0157
6	0.7-0.8	0.0138
7	0.8-1.1	0.0730

There are six sensors for each channel. The sensors use sequential scan lines placed in series (i.e., 1, 2, 3, 4, 5, 6, 1, 2, etc.) to make up the particular channel signal. This means that as a channel is observing a particular portion of the earth, its output is first from sensor 1, then sensor 2, etc. In order to have a uniform output from a given channel (assuming uniform radiance up to the optics), it is necessary to have each of the six sensors making up that channnel in identical, non-varying calibration. Unfortunately, this invariance is not always accomplished. Often, one sensor slightly alters its sensitivity with respect to the others, and the results may be a line of higher or lower apparent radiance. This effect, which is called "stripping," occurs frequently enough to cause some processing and/or interpretation difficulties.

The output for each channel (each sensor) is nearly linearly proportional to the incoming radiation. This output is then quantized into steps (counts) for ease of telemetering the data to earth. The maximum allowable number of counts for the ERTS-1 channels MSS-4, 5, and 6 is 127; only 63 counts are used for the maximum for channel MSS-7. (The sensitivities shown in Table 1 are given in radiance/count to show the minimum step-change observable.) Some of the results of this quantization and lack of perfect linearity are as follows:

(1) Channels MSS-4, 5, and 6 have only 127 steps of radiance (this must serve for surfaces whose reflectivity vary from a very few percent - like water and oil - to surfaces of very nearly perfect reflectance)

(2) Channel MSS-7 has only 63 steps of radiance

(3) When the radiance data is received by the user, a linearity correction, which often results in purposeful skipping of some count levels to approach better linearity, has already been made.

Other problems contained in the data as received by the users are electronic noise and back-background noise. Electronic and background noises are partially eliminated by the preprocessing before the data are received (along with the linearity correction). But some of the noise is still present. This manifests itself as small random variations (±2 counts for channels MSS-4, 5, and 6 and ±1 count for channel MSS-7). The background noise raises the total count level above the zero level when no radiance is seen by the detectors. This may also amount to a few counts, especially for channels MSS-4 and 5. The results of these two types of noise are to decrease the chances of seeing the small percentage change (maybe 1-2%) which may be the only difference between oil and water.

The radiance data used for this work were in the form of computer-compatible magnetic tapes. Therefore, almost all processing and analysis were done by computer-programming techniques.

2.3 RADIATION SOURCES FOR ERTS-1

There are many sources of radiant energy (both useful and not useful) seen by the ERTS-1 satellite. The multispectral scanner can detect and quantify radiant energy within the wavelength limits of 0.5-1.1 micrometers (μm). Within these limits, energy is received from the sun and sky that is specularly and diffusely reflected from the target (spot on the earth that the optics are looking at). The optics also receive scattered radiation from clouds, atmospheric particulate matter, and areas on the earth's surface near the target.

Of these various energy sources, the specularly and diffusely reflected radiation carries the most information. This radiation helps identify the target as to material and condition of material. It is this information that is used to interpret ground targets by remote sensing.

The other energy sources serve to raise the background level of the output and mask small changes in the target material (or reflectivity).

Along with these undesirable energy sources, the conditions of the earth's atmosphere must be taken into account. The atmosphere absorbs energy (decreasing useful information from the target), scatters energy (both into the optical path from extraneous sources and out of the path from the target), and—to a smaller degree—reemits energy.

All these negative effects are dependent on (1) the zenith angle of the sun (length of atmosphere through which the sunlight must travel), (2) the angles between the sun, the target, and the satellite, and (3) the wavelength of the radiant energy.

For interpretation of oil-water situations, most of these negative effects arise. The solar-zenith angle and the angles between the sun, the target, and the satellite must be considered to minimize the effects of atmosphere and of sun glint off wave surfaces. Clouds and haze may cause scattering effects that overshadow the effects being sought. Nearness of land will also overshadow the very low oil/water reflectances, especially for rivers or turbid coastal waters.

3
ATLANTIC SPILL

This chapter describes the spill off the Virginia coast and discusses the analysis and results of the ERTS-1 data processing for this event.

3.1 PHYSICAL DESCRIPTION AND LOCATION

Information regarding this spill was brought to our attention by an article appearing in "Remote Sensing of the Environment" [6]. This spill was noted in ERTS-1 frame #1348-15082 (of 6 July 1973). There is no eye-witness report of the spill, and no ground data have been found

to identify or describe the material as to thickness, concentration, or water quality surrounding the spill. The source of the spill is still unknown.

The spill was located about 74°30' East longitude, 37°30' North latitude. This is 90-100 km east of the coast of Virginia in the Atlantic Ocean (about 160 km northeast of Norfolk, Virginia). The total length of the spill is about 60 km (not continuous), and it has a maximum width of 3 km (see Figure 1).

ERTS-1 passed over the area about 10 am (local), and sun was 61° above the horizon. The scene near the center of the spill is fairly clear, but clouds and haze are at both the northern and southern ends.

The length of time the spill had been on the water before the ERTS-1 overpass is not known. Meteorological data covering the 36 hours before the overflight show the average wind speed was about 3 m/sec and steady, but the direction was gradually changing from out of the west to east during that time.

3.2 METHOD OF ANALYSIS - SPECTRAL SIGNATURES

Clear conditions over the central spill area suggested an attempt to derive spectral signatures by statistical means. As no ground data for the spill were available, only the satellite data could be used to generate these signatures. The general procedure was to identify as many different regions of the spill (and its environs) as possible, then combine those areas whose signatures were nearly identical.

The first step in the analysis is to smooth out the random and systematic fluctuations in the data caused by electronic or detector noise. This is done by redefining the data value at each point (pixel) as being the average value of a grid of points, two pixels wide by 6 pixels long. This average value is said to be the value of the pixel in the upper left corner of this 2 × 6 grid. This procedure is designed to eliminate the variations of the six sensors/channel as well. Misrepresentations can occur at the edges both of the tape data and of a sharp discontinuity in ground reflectance. However, these errors usually have only minor consequences.

The next step in the process of finding signatures is to identify as many different types of targets as possible, and then find the radiance value for each channel for all the pixels within each target type. The average value (mean) of radiance for each channel, together with the standard deviation from the mean for all pixels of the same target type, make up the spectral signature for that target type. Because of the large number (more than 100) of signatures originally generated, some were grouped together if their means were close in all four channels. This reduced the number of signatures to 17. These 17 spectral signatures are shown in Table 2.

Figure 2 is a recognition map showing the location of each of the target types. For ease of display, some of the types that still had similar signatures were grouped together for this

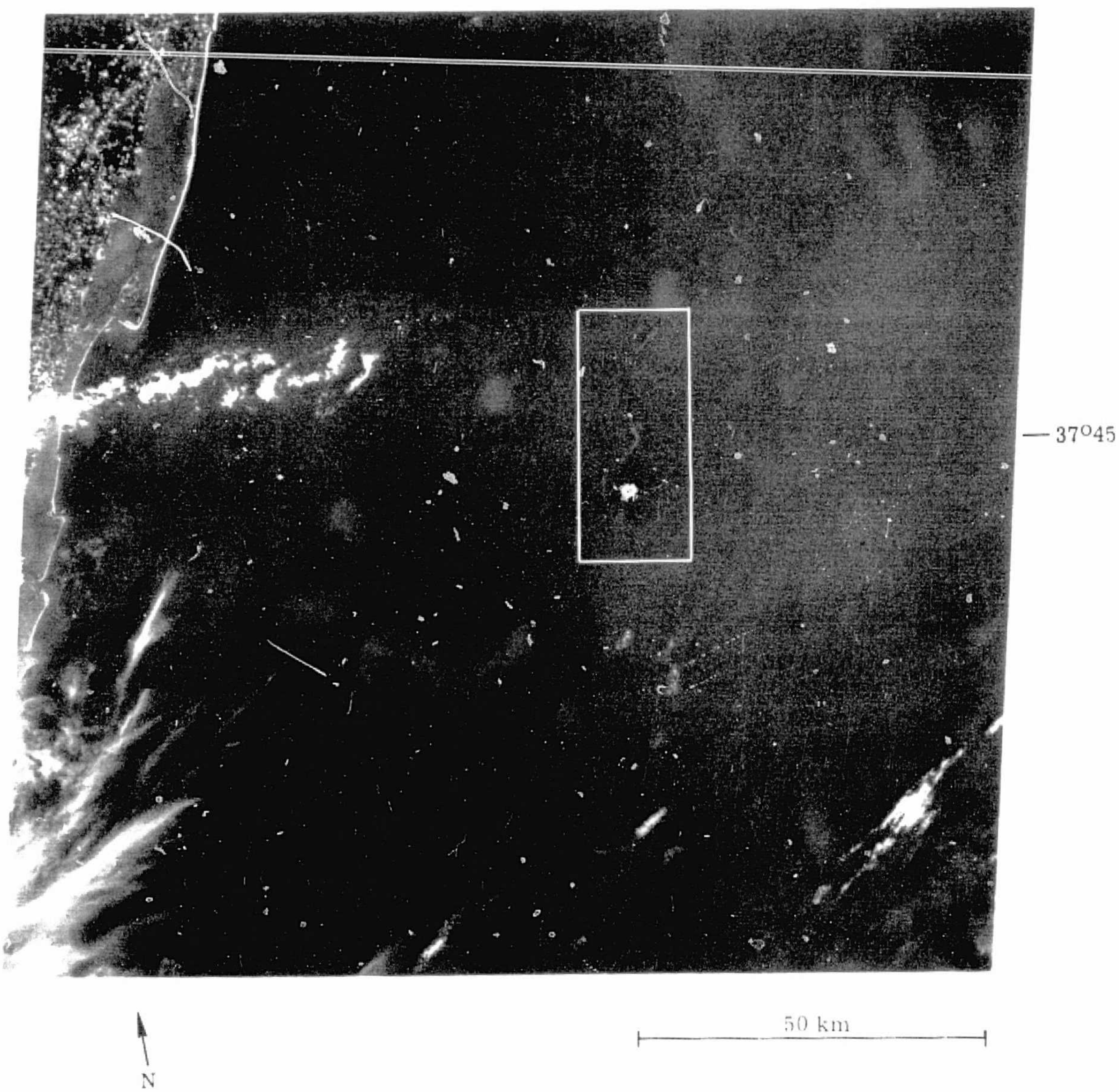

FIGURE 1. LOCATION OF ATLANTIC-OCEAN SPILL. ERTS frame E-1348-15082, 6 July 1973, channel MSS-5, center frame coordinates: 37°26'N, 74°42'W.

TABLE 2. FINAL SIGNATURE VALUES (DATA COUNTS) OF MEAN AND STANDARD DEVIATION FOR EACH ERTS-1 CHANNEL

Target Type	Signature #	MSS-4 Mean	MSS-4 Std. Dev.	MSS-5 Mean	MSS-5 Std. Dev.	MSS-6 Mean	MSS-6 Std. Dev.	MSS-7 Mean	MSS-7 Std. Dev.
Dark blotch	DB	31.9	0.3	19.7	0.4	12.4	0.2	3.2	0.2
Water	WA	32.7	0.3	20.8	0.2	13.2	0.2	3.6	0.2
Edge spill	E1	33.7	0.3	21.5	0.2	13.6	0.2	3.6	0.2
Edge spill	E2	33.5	0.1	21.8	0.2	14.0	0.1	4.0	0.1
Edge spill	E3	34.2	0.3	21.9	0.2	14.0	0.2	3.9	0.2
Edge spill	E4	34.0	0.2	21.0	0.1	14.4	0.1	4.0	0.2
Edge spill	E5	34.5	0.2	22.3	0.2	14.5	0.2	4.0	0.1
Edge spill	E6	35.1	0.2	22.2	0.2	14.4	0.2	4.0	0.1
—	M1	34.9	0.4	22.7	0.2	14.8	0.2	4.1	0.2
—	M2	35.2	0.2	23.1	0.2	15.4	0.2	4.3	0.2
—	M3	35.7	0.2	23.0	0.3	15.1	0.3	4.2	0.2
—	M4	36.1	0.3	23.4	0.3	15.5	0.2	4.3	0.2
—	B1	36.2	0.4	23.9	0.2	16.0	0.2	4.5	0.2
—	B2	36.5	0.3	24.4	0.2	16.6	0.3	4.8	0.2
Center spill	CS	37.4	0.6	25.9	0.6	18.1	0.3	5.5	0.2
Cloud-2	C2	45.6	1.1	33.7	1.4	24.8	1.2	8.5	0.6
Center cloud	CL	50.3	1.2	40.5	2.3	30.8	2.0	11.1	0.9

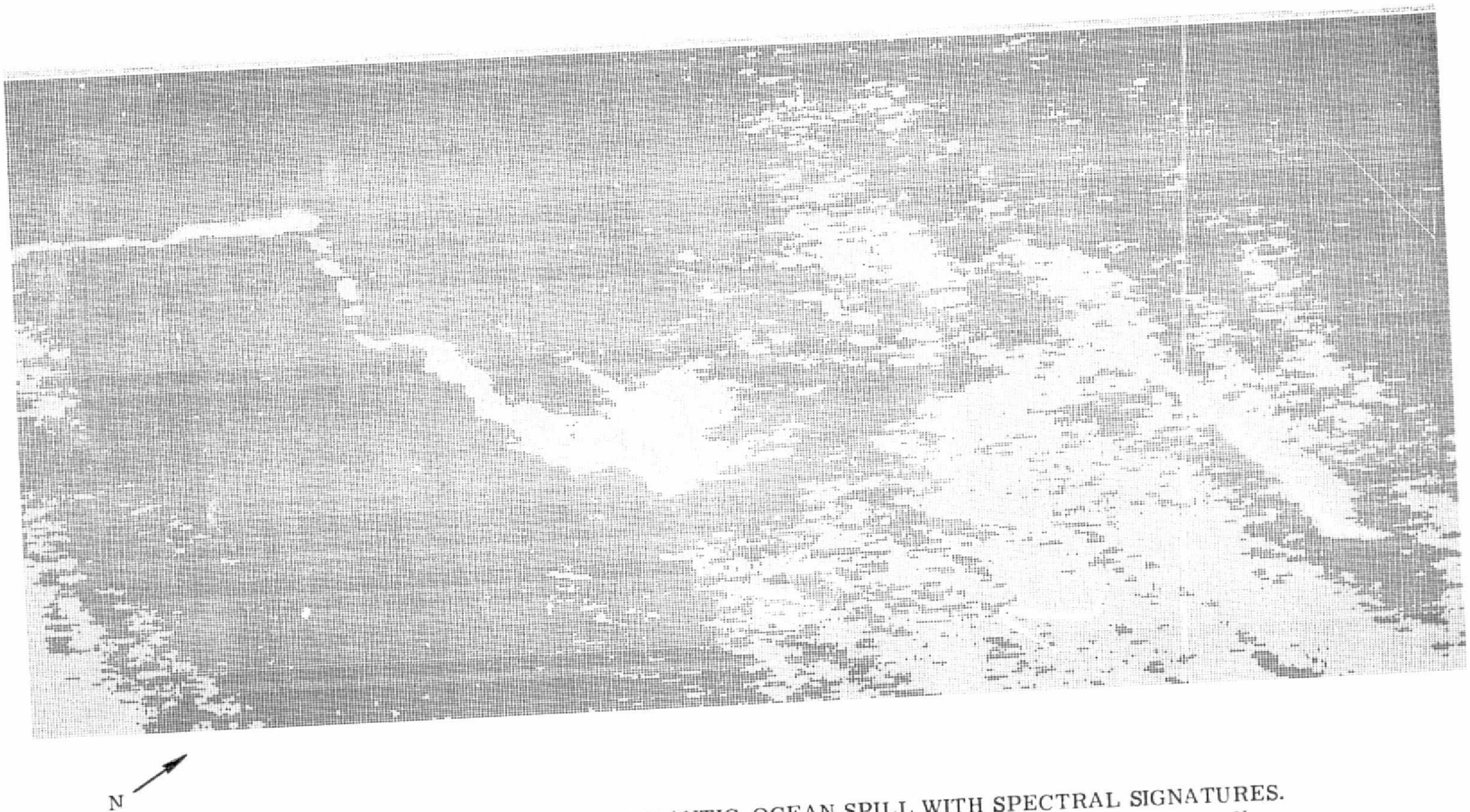

FIGURE 2. RECOGNITION MAP OF ATLANTIC-OCEAN SPILL WITH SPECTRAL SIGNATURES. Area covered is about 15 km by 70 km; the darker the symbol, the lower the reflectance in all channels.

display. The brightness of the different areas of the map are an indication of relative lighter (higher reflectance) or darker areas, with all channels compared simultaneously.

3.3 RESULTS OF SPECTRAL-SIGNATURE METHOD

By using the spectral-signature generating method of analysis on this spill, the following products were obtained: recognition map, mean and standard deviation for each signature for all ERTS-1 channels, inter-channel comparisons of data, and spectral data for each of the signatured types of materials.

The recognition map in Figure 2 displays a portion of the area studied. It should be noted that all 17 signatures are not displayed separately on the map, but rather some very close signatures are combined to avoid confusion and increase visibility. Some noteworthy features of the map are (1) the very bright spot at the center of the spill, (2) the gradual brightening of the spill toward the central spill area, (3) the long tail of material south of the large spill area, (4) the cloud and haze in the north and south, (5) the darker non-contiguous blotches running across the tail of the spill, and (6) the second, less distinct large area of spill north of the primary spill and mixed in with the clouds and haze.

As discussed in the theory section (Chapter 2), an oil spill usually becomes darker as the thickness of the oil increases. Because of the volitility, viscosity, and surface tension of petroleum products, this usually means the thicker area is nearer to the center of the spill than to the edge. However, some petroleum spills have been seen to be brighter at or near the center [7, 8]. In addition, because of the difference in reflectivity of different petroleum products [3] different materials have different reflectivity and, therefore, may result in brightness variations depending on both the material and its thickness. Furthermore, non-petroleum products can also produce effects such as those seen in this spill. Therefore, it is impossible without ground data to positively identify the material as being a specific type of petroleum product, many different petroleum products, or even petroleum products mixed with non-petroleum products.

The darker blotches running across the central spill are also difficult to explain. One possible explanation is that this spill has started to break up and left small thick spots. The darkness may result from a lack of backscatter from the water caused by the material's thickness, or from a lack of surface-roughness elements caused by wave calming. Spectrally, the non-contiguous dark area is definitely darker than water in all the spectral channels.

Table 2 shows the values of the mean and standard deviation from the mean for each of the signatured materials. A noteworthy feature of this table is the closeness of most of the signatures (the variation of the mean values for each channel for most of the signatures differs by only a few counts for all but a few of the signatures).

Another feature seen is the relatively low count value (the ERTS-1 spectral scanner can indicate up to 127 counts in channels MSS-4, 5, and 6 and 63 counts in channel MSS-7). In the case of channels MSS-4, 5, and 6 all values were less than 40, 30, or 20 respectively (except for cloud areas), and channel MSS-7 had all values less than 6 counts (except for cloud areas). Because of these small values, and small differences between values, it may be very difficult to assess the true differences between the material types.

It is possible to point out the differences between the central spill area and the background water. The central spill has data values higher than that of the water (up to 50% higher in some channels). This difference can be attributed only to a definitely higher reflectance material than water. Of course, the cloud and haze areas have much higher reflectance than either the water or the spill.

To compare the different signatures and their potential overlap with each other, as well as the relation between any two or more channels, two methods are used.

The first method involves looking at the possible overlap between data points in one signature versus data points in another. This is shown in Figure 3. The average pair-wise probability of misclassification of a data point from one signature to another was computed. The values listed in the figure are percent of probable misclassification—rounded to the nearest whole percent. To understand the significance of any particular number, let us take an example.

If we want to find the probability of misclassification of the water (WA) with that of the edge of the spill (EI), we look up the intersection of these two signatures. The value given in the figure is 2%. This means that there is an average probability of 2% that data points in the water signature should be in the spill-edge signature, and that points in the spill-edge signature should be in the water signature. Note that this is an average of both events occurring.

It is worthy of mention that the highest value indicated in the table is only 10%. This value lies between two signatures that are very close in their identification; in fact, they might have been assumed to be within the same signature had further analysis been carried out.

Some significant features of this figure are that the large number of zeroes indicate many very distinct signatures. (This is somewhat surprising in light of the small differences in the data values for each signature.) However, this can possibly be explained by recalling that a signature considers all four channels, which results in a better identification than can be made by using only one or two channels. Another feature of this figure is that the central spill area (CS) has zero probability of misclassification with any other signature. In fact, the only significant inter-signature misclassifications that might occur are those that appear physically close to each other on the map in Figure 2. In some cases, these signatures are actually

PROBABILITY (%)

SIGNATURE NUMBER	DB	WA	E1	E2	E3	E4	E5	E6	M1	M2	M3	M4	B1	B2	CS	C2	CL
DB																	
WA	0																
E1	0	2															
E2	0	0	5														
E3	0	0	6	3													
E4	0	0	1	2	7												
E5	0	0	0	0	6	4											
E6	0	0	0	0	2	0	7										
M1	0	0	0	0	0	0	4	5									
M2	0	0	0	0	0	0	0	0	2								
M3	0	0	0	0	0	0	0	1	6	9							
M4	0	0	0	0	0	0	0	0	0	2	10						
B1	0	0	0	0	0	0	0	0	0	0	0	4					
B2	0	0	0	0	0	0	0	0	0	0	0	0	4				
CS	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
C2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
CL	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	
	DB	WA	E1	E2	E3	E4	E5	E6	M1	M2	M3	M4	B1	B2	CS	C2	CL

SIGNATURE NUMBER

FIGURE 3. AVERAGE PAIR-WISE PROBABILITY (%) OF SIGNATURE MISCLASSIFICATION FOR ATLANTIC SPILL

combined on the map because of their small differences in radiance from each other. Signatures E1 and E2, signatures E3, E4, E5, and E6, signatures M1 and M2, signatures M3 and M4, and signatures B1 and B2 are combined as separate groups on the map in Figure 2. Combining the sets as such eliminates more than half of the probability of misclassification as shown in Figure 3.

Another feature of the figure is that signatures E3 and M3 appear to have the largest probability of misclassification with any of the other signatures. However, each of these two signatures have only 1/4 of their data points that may be misclassified. And, again, the misclassification would set the extraneous data points into immediately adjacent signatures. The last item to note on this figure is that all the non-zero elements occur on or near the central diagonal. Again, this is another indication that the only errors in misclassification seem to occur between signatures very closely situated in terms of their mean radiances. Had fewer signatures been chosen, or a larger standard deviation allowed each mean, there is even less likelihood of the misclassification being as large as it is.

Figures 4-6 show the other means of comparing signatures with their means, standard deviations, and the variations within the different ERTS-1 spectral channels. In each of these figures, the data value for the ERTS-1 channel is shown along the abscissa, while the data value for a second channel is shown along the ordinate. In all cases the scales are the same. The only difference in appearance is the degree of suppression of the zero in each channel. Again, we can see some signatures tend to overlap others, whereas some are quite distinct. We can also see why some individual signatures might be grouped into an even larger, slightly more diverse signature.

In these figures the cloud signatures are not shown, as their signatures are so different from the others that it was not necessary to display them. Furthermore, their composition is made up of such diverse reflectivities that no new information could be obtained by including them.

The most significant features of these three figures are the slope of the best-fit line through the means and the spread of the points from lower left to upper right. As the slope approaches unity, from either above or below, the channels approach maximum inter-channel correlation. A given increase in one channel will produce the same or similar magnitude change in the other. Of course, this change is based on absolute values of data counts and not on radiance or percent increase. (In the case of channels MSS-4, 5, and 6, however, their values of radiance per count is very similar.) The other parameter was the spread from lower left to upper right. As the spread increases, the inter-channel comparison is better. A small spread indicates little change in one channel with respect to another. Looking at these figures, it can be seen that for water and spills on water the best channels from

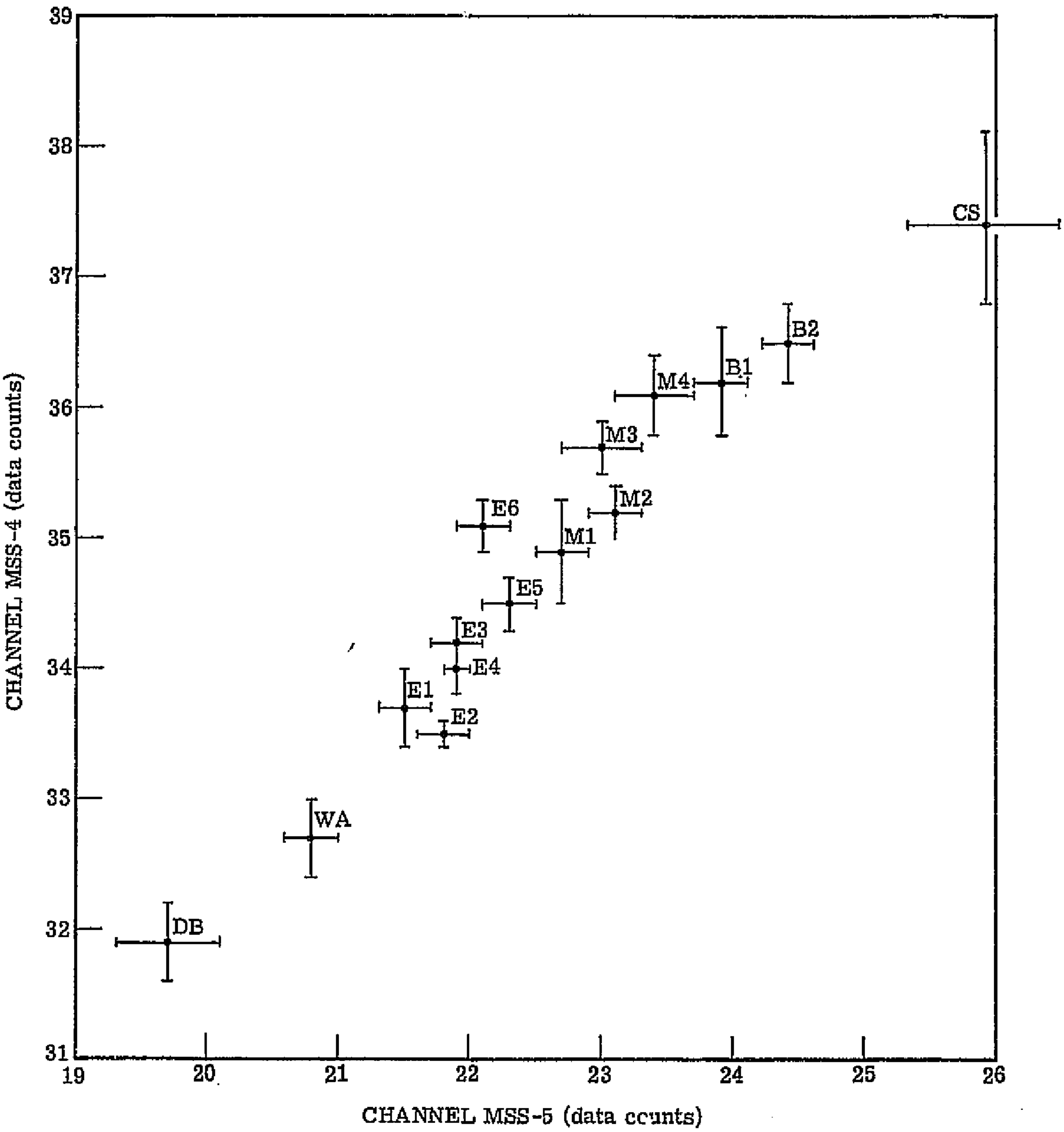

FIGURE 4. MEANS AND STANDARD DEVIATIONS OF SPECTRAL SIGNATURES FOR ATLANTIC-OCEAN SPILL: COMPARISON OF ERTS-1 CHANNEL MSS-4 AND MSS-5

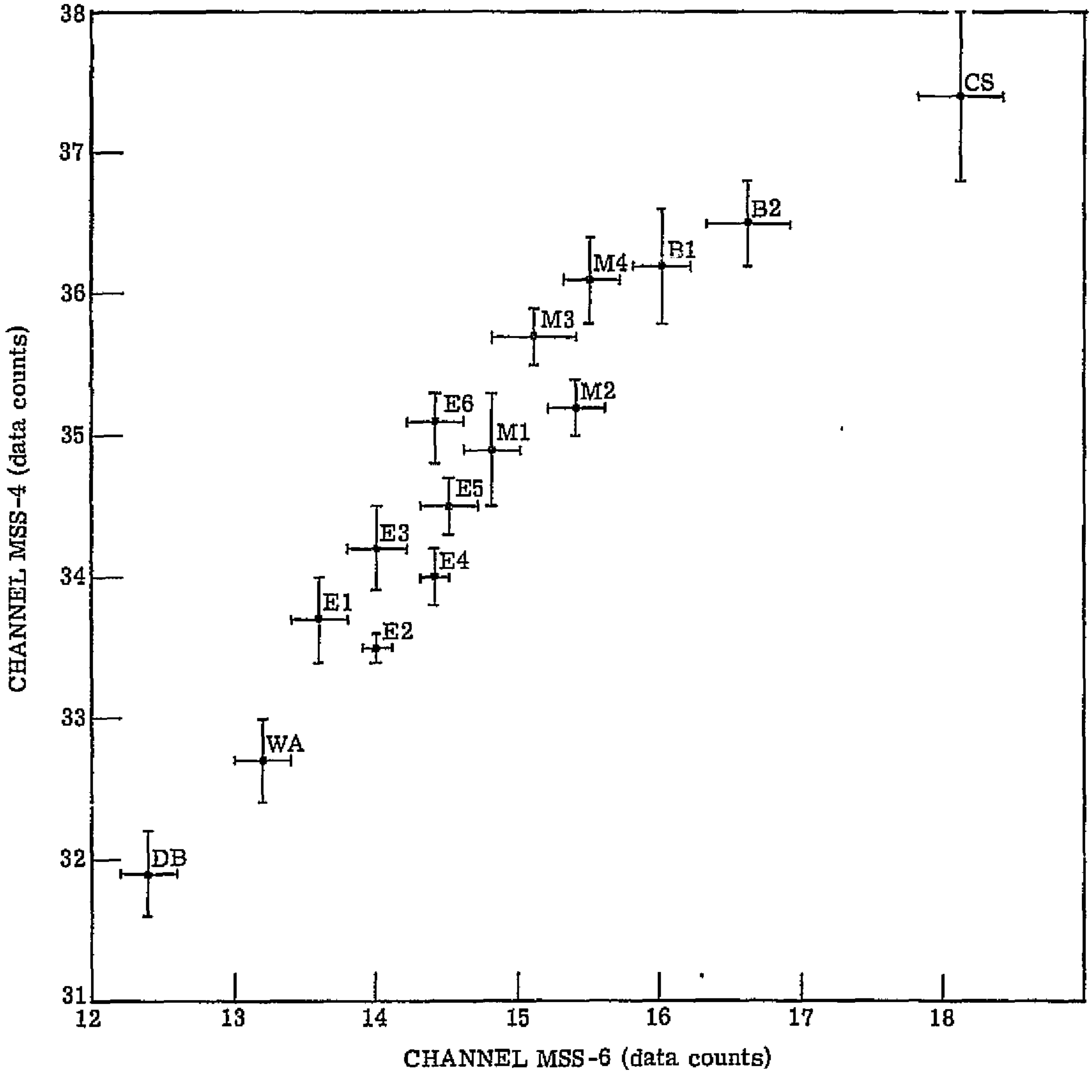

FIGURE 5. MEANS AND STANDARD DEVIATIONS OF SPECTRAL SIGNATURES FOR ATLANTIC-OCEAN SPILL: COMPARISON OF ERTS-1 CHANNELS MSS-4 AND MSS-6

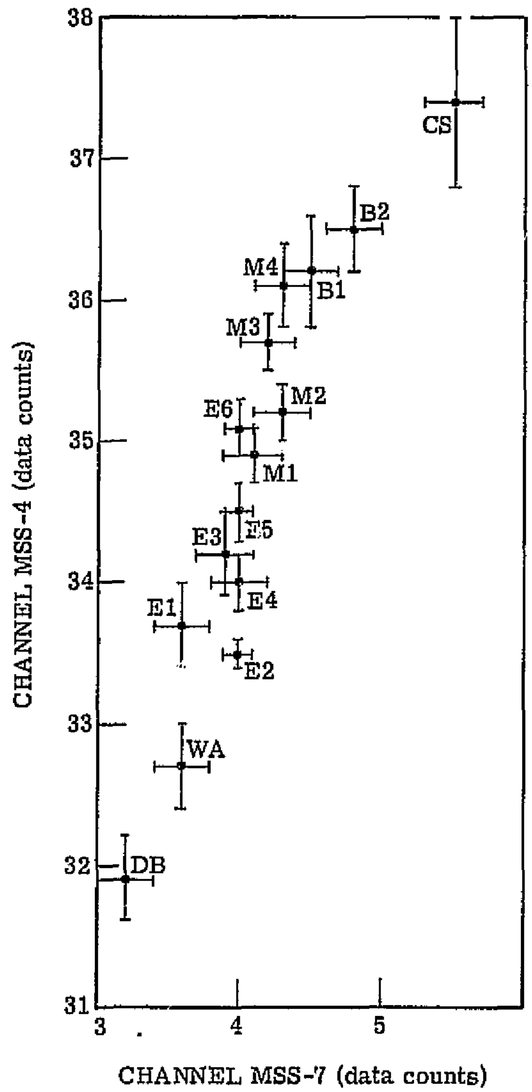

FIGURE 6. MEANS AND STANDARD DEVIATIONS OF SPECTRAL SIGNATURES FOR ATLANTIC-OCEAN SPILL: COMPARISON OF ERTS-1 CHANNELS MSS-4 AND MSS-7

the ERTS-1 system to use for maximum information are MSS-4, 5, and 6. This is another way to show the same thing that has been said throughout this report.

In order to evaluate some characteristics of the spill, it is now necessary to look at the signatures and analyze their spectral features. Figures 7 and 8 show the radiance for each ERTS-1 spectral channel as a function of wavelength for four typical (important) signatures. The signatures chosen for this analysis were (1) the background-water signature, (2) the dark blotchy area, (3) the edge of the spill, and (4) the central-spill area. In Figure 7 we see the actual radiance values (received by the satellite) and how they differ from one signature to another. The dark area is seen as being slightly lower in radiance than water in all cases. The edge of the spill is slightly higher than water in all cases. And the central-spill area is always higher than water, by a somewhat larger amount. Figure 8 has the same abscissa of wavelength showing the ERTS-1 spectral channels, versus a relative-radiance scale (water equals unity) along the ordinate. Again, we see the darker area is lower than water, and the negative difference increases as the wavelength increases. The edge of the spill can be seen to have a slightly higher radiance (reflectivity) in all channels. This may be the result of (1) the material being well mixed with the water or (2) the edge material being made up of a mixture of the spill material and water, which would give it most of the characteristics of water due to the dilution.

The final area shown on this figure is that of the central spill. This is always higher in radiance than water. In fact, it increases from about 16% higher to more than 50% higher as the wavelength increases. The material appears to be little mixed with water and to have many of the characteristics of a moderately thin (a few micrometers) spill of a heavy petroleum product [3].

3.4 CONCLUSIONS OF ATLANTIC-SPILL ANALYSIS

The conclusions that may be reached regarding the analysis of the spill in the Atlantic Ocean off the Virginia coast are as follows:

(1) Analyzing digital ERTS-1 data by means of spectral-signature differentiation can separate a few distinct areas of material on the water

(2) The analysis using spectral signatures (the method) is probably much more precise than the original data warrants

(3) The value of the ERTS-1 channels for identifying material spilled on ocean water is questionable, since the low data values, the large bandwidths, and the few number of bands allow only coarse estimates as to the identity of the material

(4) Beacuse the source of this dumping is unknown and there is no ground truth available for material identification or characteristics such as thickness and appearance, it is not possible to assign any probability to the identification of the products seen on the water

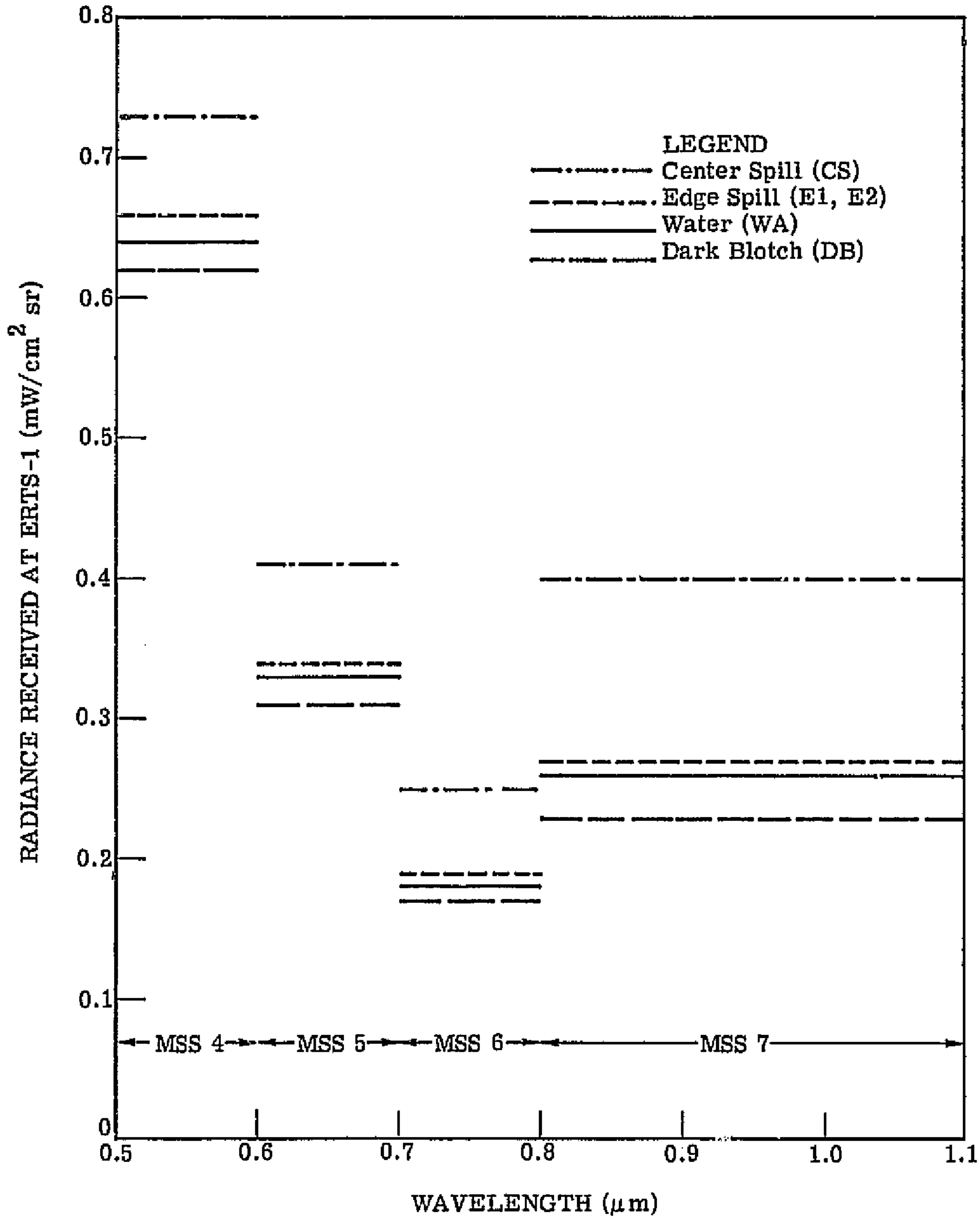

FIGURE 7. SPECTRAL CHARACTERISTICS FOR FOUR OBSERVED SIGNATURES OF ATLANTIC SPILL

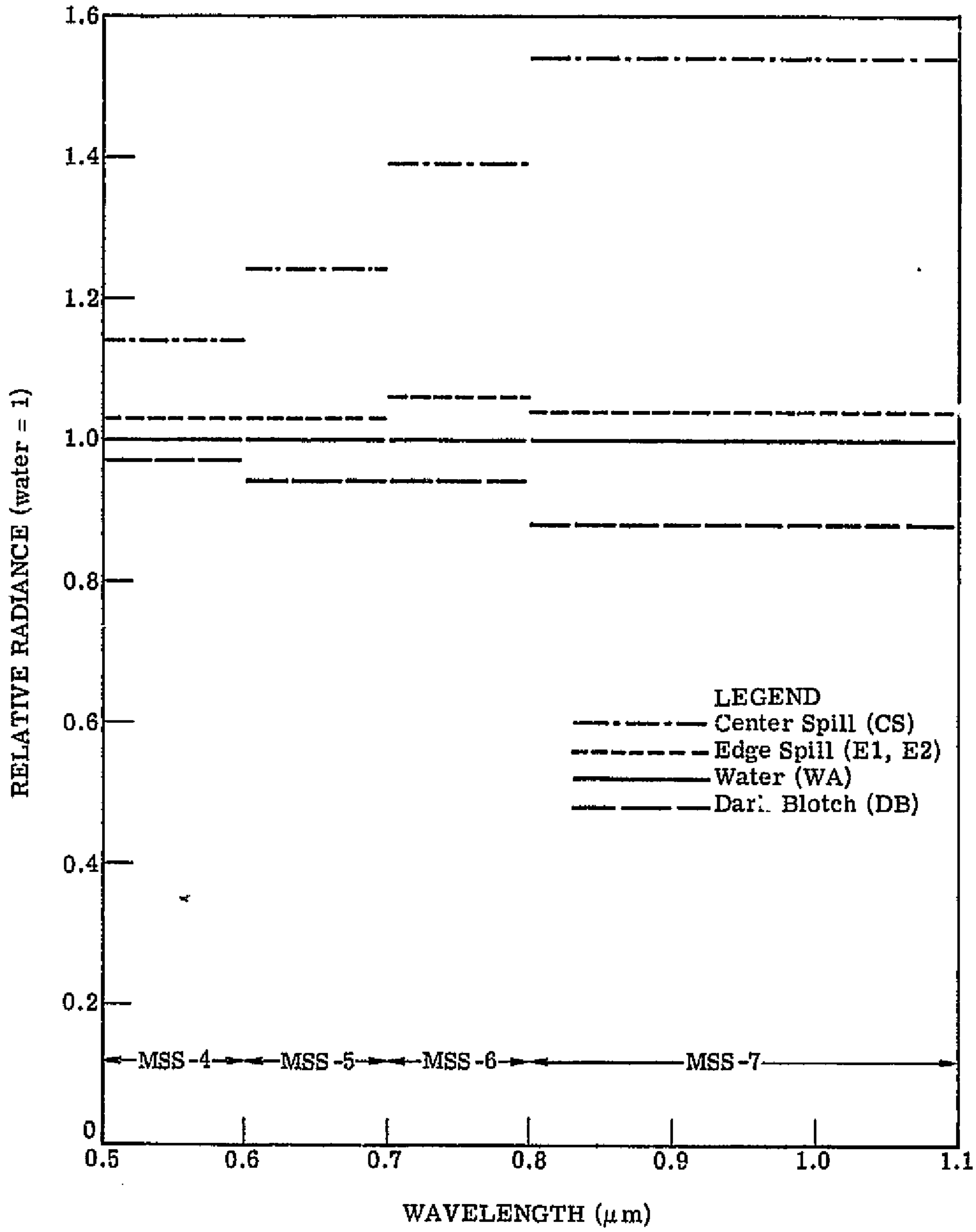

FIGURE 8. SPECTRAL CHARACTERISTICS FOR THREE OBSERVED SIGNATURES OF ATLANTIC SPILL (RELATIVE TO WATER)

(5) All spectral and spatial characteristics observed could have been produced by a spill of petroleum substance (crude or processed) from a moving vessel.

4
OAKLAND-BAY SPILL

This chapter describes the oil spill in Oakland Bay and presents the analysis and results of the ERTS-1 data processing for this spill.

4.1 PHYSICAL DESCRIPTION AND LOCATION

Information regarding this oil spill was obtained from the pollution reports of the United States Coast Guard and the Environmental Protection Agency. The oil spill was originally reported on 19 January 1973 and lasted until 24 January 1973. It was the result of spillage of 454,000 liters (120,000 gallons) of waste oil just west of Government Island in the inner harbor of Oakland Bay. The spill ultimately moved out into the outer bay. Because of the good documentation of the spill, the ERTS-1 overpass of 22 January 1973 (frame #1183-18175) was used to analyze this event. For this imagery, the sun was 26° above the horizon and the local time was about 10 am. The area is located about 37°45' north latitude, 122°45' west longitude. Although there was some cloudiness and haze on the imagery, the area we were investigating appeared very clear (see Figure 9).

4.2 METHOD OF ANALYSIS - RATIO OF SPECTRAL CHANNELS

Two methods of analysis were attempted on this oil spill. The method of radiance summation is evaluated in the following sections of this chapter. This section deals with the method of ratioing the radiance of different spectral channels.

It was shown by Yarger [9] and others that some quantitative assessment of the degree of turbidity in water can be made by computing the ratio of the radiance in two different spectral channels. In his work Yarger simply computed ratios of the data-count levels from combinations of ERTS-1 channels (two at a time) and then made an empirical best-fit curve to compare these ratios with the actual ground-measured suspended inorganic load in the water. Our concern in this section is to try to separate the effects of the turbid nearshore waters of the inner harbor and the bay from the effects of the floating oil slick. To do this, some criteria had to be established concerning what ratios could be used and what they would indicate.

The following criteria were used to calculate ratios. First all data were converted from data counts to radiance for all channels. Second, in order to eliminate background effects, an open ocean-water area was used to determine a baseline level of radiance. This would be the

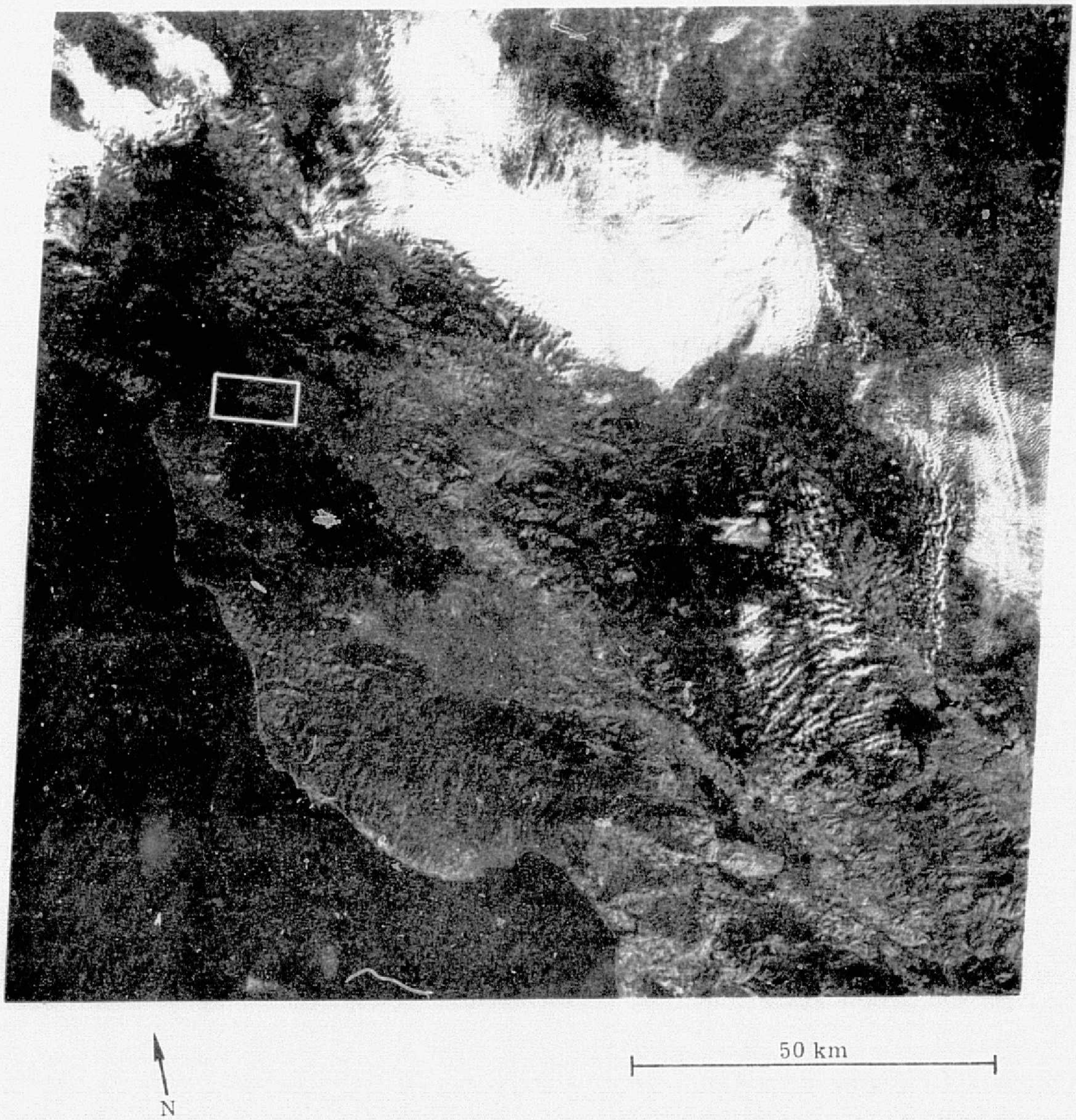

FIGURE 9. LOCATION OF OAKLAND-BAY SPILL. ERTS frame E-1183-18175, 22 January 1973, channel MSS-6, center frame coordinates: 37°32'N, 121°47'W.

radiance level if suspended material and oil were not in or on the water. This baseline level was then subtracted from all investigated areas in order to look at the remainder, regardless of the cause. After the subtraction was completed, the ratios of MSS-4/MSS-5, MSS-4/MSS-6, and MSS-4/MSS-7 were calculated for the 12 sites shown in Figure 10. The average data values for the sites, the radiance levels, the radiance levels minus the background, and the ratios are all shown in Table 3 for the 12 sites, and the open ocean water. Each of the 12 area samples were defined by averaging over a region containing an integer multiple of six scan lines in order to eliminate sensor variability.

From parametric curves such as Ramsey's [10], it can be seen that the values of radiance for channels MSS-4 and 5 would both increase as the amount of floating algae near the surface of the water increased. However, the ratio of MSS-4/MSS-5 would always be greater than unity if the algae were the dominant reflecting material. For the case of suspended inorganic material, such as clay and silt, we refer to references such as Polcyn and Rollin [11], which show that as the turbidity increases, the reflectance increases—as expected. However, the reflectivity of MSS-4 is much less than MSS-5 and their ratio would be less than unity. Again, it must be pointed out that in both these cases we are assuming that we have eliminated the baseline radiance.

In the case of oil on the surface of water, finally, oil has a reflectivity that is essentially the same shape as that of water (not much change in reflectance with respect to wavelength); in this case, then, the ratio of MSS-4/MSS-5 should be about unity.

4.3 RESULTS OF SPECTRAL-RATIO METHOD

Comparing the ratios of MSS-4/MSS-5 from Table 3, all cases were considerably less than unity, varying from near 0 to about 0.6. This shows that the dominant reflective characteristic in the water is suspended inorganic material. It is then extremely difficult, if not impossible, to see the slight difference in reflectance caused by oil sitting on the surface of such water.

Another variable that must be considered is the amount of light that can be scattered from surrounding land (with higher reflectance) up into the optical path of the satellite's optics and appear to come from the target area. This amount of error resulting from ground scatter increases as the difference in reflectance between the target and its surroundings increases. The error also increases as the target becomes small relative to its surroundings. For these reasons, the radiance values of sites 9, 10, 11, and 12 should all be expected to be higher than that of open water, especially in channel MSS-7, which is most sensitive to land. A look at Table 3 shows this to be the case.

Examples of this effect are seen in Goldman [12]. Assume the sun is 30° above the horizon, the atmospheric visibility is 23 km, and the wavelength used is 0.55 micrometers. Now let our

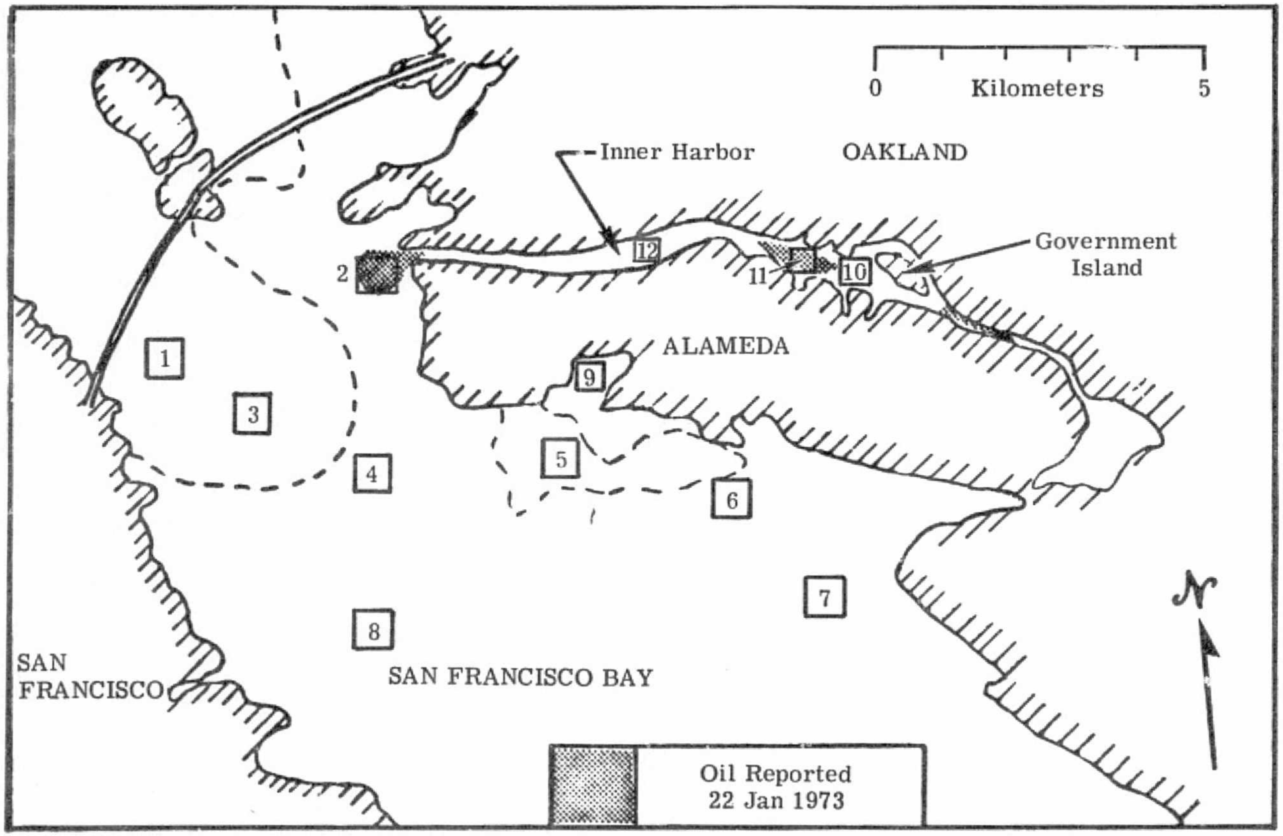

FIGURE 10. INVESTIGATED SITES IN OAKLAND-BAY AREA

TABLE 3. AVERAGE DATA VALUES, RADIANCES, AND RATIOS FOR SITES NEAR OAKLAND-BAY SPILL

	Test Site Average (data counts)				Test Site Average Radiance Minus Water ($\mu m/cm^2 sr$)				Ratio		
Test Site #	MSS-4	MSS-5	MSS-6	MSS-7	MSS-4	MSS-5	MSS-6	MSS-7	MSS-4/MSS-5	MSS-4/MSS-6	MSS-4/MSS-7
1	20.27	14.38	6.71	0.53	59	98	47	29	0.5	1.0	1.7
2	18.94	11.75	4.91	0.25	33	56	27	9	0.6	1.2	3.7
3	20.13	13.94	6.25	0.33	57	91	41	15	0.6	1.4	3.8
4	17.88	9.83	4.07	0.39	13	26	11	19	0.5	1.4	0.7
5	19.74	13.50	6.55	0.62	49	84	45	35	0.6	1.1	1.4
6	19.35	12.44	5.50	0.50	42	67	31	27	0.6	1.4	1.6
7	17.25	9.05	3.65	0.42	1	14	5	21	0.1	0.2	0.05
8	18.22	11.05	4.50	0.42	20	46	17	21	0.4	1.2	1.0
9	17.64	9.92	4.56	0.47	8	28	18	25	0.3	0.4	0.3
10	16.93	9.52	4.23	0.64	-6	22	13	37	-0.3	-0.5	-0.2
11	17.14	9.66	4.46	0.70	-2	24	16	41	-0.1	-0.1	-0.05
12	17.25	9.80	4.55	0.47	1	26	18	25	0.04	0.1	0.04
Water	17.22	8.15	3.27	0.13	—	—	—	—	—	—	—

target have a reflectance of 6% (similar to oil or water) and allow its diameter to vary from 100 m, 500 m, 5,000 m, and 50,000 m. Furthermore, let the target be sitting inside a different material that extends to infinity in all directions. This background material has a reflectance of 12% (similar to shore). The values of the ratio of the radiance reaching the satellite from the background divided by that from the target are shown in Table 4.

This is a hypothetical example, but it does point out the difficulty in looking at oil on water. It also shows why it is nearly impossible to see small changes in the water's reflectance near shore or in rivers.

4.4 METHOD OF ANALYSIS - SUMMATION OF RADIANCE

As indicated previously in this chapter, other methods were used to analyze this oil spill. The method discussed in this section is the summation of radiance. The theory section of this report (Chapter 2) points out that for a thin oil spill, the reflectivity of the spill is slightly different from that of water. This method considers such a difference in trying to locate areas whose reflectance has changed because of an oil film on the surface of the water. The areas discussed at the beginning of this chapter (see Figure 10) are again used to distinguish those sites having oil on them from those that do not. The radiance values from Table 3 were used to evaluate the 12 sites.

The method of radiance summation is used in an effort to overcome detector and electronic noise. It is felt that by adding the radiance values of different channels, there will be only a slight random noise added to the total signal of the different channels. This will minimize the noise while maintaining the signal.

Radiance values for six cases were taken; MSS-4 and 5, MSS-4, 5, and 6, MSS-4, 5, 6, and 7, MSS-4, 5, and 7, MSS-4 and 7, and MSS-5 and 7. Table 5 shows the results of these summations for the 12 areas as well as the relative ranking for each area. The ranking, which is placed in parenthesis next to the radiance value [0.553(3)], indicates whether the site is high in radiance compared to the others (1) or low (13). The ranking of the non-summed initial radiance values for each site and channel is also shown.

4.5 RESULTS OF RADIANCE SUMMATION

According to the ground data, oil was observed at sites 2, 11, and maybe 10 (with only a slight sheen seen at the latter two). Verification of this information is now attempted.

Table 5 shows that in all cases in which two or more spectral channels were summed, sites 1, 5, 3, and 6 were always those with the highest radiance. In none of the summation cases were sites 2, 10, or 11 in the highest four. In fact, these three sites seem to have sums near the central values in most cases. Site 2 is fairly high in radiance compared to the other two, except in channel MSS-7. For that channel, sites 10 and 11 are the highest. This is not surprising in light of the discussion (Section 4.3) regarding near shore difficulties.

TABLE 4. VARIATION IN SATELLITE RADIANCE FROM TARGET AS TARGET DIAMETER INCREASES. Sun is 80° above horizon, visibility is 23 km, wavelength is 0.55 μm; target is 6% reflector, background is 12% reflector.

Target Diameter (m)	Radiance from Background/Radiance from Target
100	0.6
500	0.5
5,000	0.4
50,000	0.3

TABLE 5. SUMMATION OF ERTS-1 CHANNEL RADIANCES AND RELATIVE RANKING [IN PARENTHESES—HIGHEST = 1] FOR OAKLAND-BAY TEST SITES

Test	Ranking for ERTS-1 Channels					Sum of Radiance ($\mu m/cm^2 sr$) for Indicated Channels and Relative Ranking			
Site #	MSS-4	MSS-5	MSS-6	MSS-7	(MSS-4) + (MSS-5)	(MSS-4) + (MSS-5) + (MSS-6)	(MSS-4) + (MSS-5) + (MSS-6) + (MSS-7)	(MSS-4) + (MSS-5) + (MSS-7)	(MSS-4) + (MSS-7)
1	(1)	(1)	(1)	(1)	621(1)	713(1)	751(1)	659(1)	433(1)
2	(5)	(5)	(5)	(12)	553(5)	621(5)	639(5)	571(5)	387(5)
3	(2)	(2)	(3)	(11)	611(2)	697(2)	721(3)	635(3)	416(3)
4	(7)	(8)	(11)	(10)	503(7)	559(8)	587(9)	531(9)	377(9)
5	(3)	(3)	(2)	(3)	597(3)	687(3)	731(2)	641(2)	429(2)
6	(4)	(4)	(4)	(5)	572(4)	648(4)	684(4)	608(4)	413(4)
7	(9)	(12)	(12)	(9)	478(12)	528(12)	558(12)	508(12)	366(12)
8	(6)	(6)	(8)	(8)	528(6)	590(6)	620(6)	558(6)	385(6)
9	(8)	(7)	(6)	(6)	500(8)	563(7)	597(8)	534(8)	378(8)
10	(13)	(11)	(10)	(2)	479(11)	537(11)	583(11)	525(10)	376(10)
11	(12)	(10)	(9)	(1)	486(10)	548(10)	598(7)	536(7)	384(7)
12	(9)	(9)	(7)	(7)	490(9)	553(9)	587(9)	524(11)	370(11)
Water	(9)	(13)	(13)	(13)	464(13)	509(13)	518(13)	473(13)	345(13)

Overall, it appears very difficult to come to any conclusion regarding the presence of oil at any of these 12 sites, much less the areas known to have oil. The overwhelming features appear to be turbid water conditions and nearness to shore. Both these effects overshadow any slight reflectance changes caused by oil on the surface of the water.

5
SOUTHERN-CALIFORNIA COASTAL SPILL

This chapter describes the oil spill off the coast of Southern California and discusses the analysis and results of the ERTS-1 data processing for this spill.

5.1 PHYSICAL DESCRIPTION AND LOCATION

Information regarding this oil spill was acquired while pursuing the pollution reports of the United States Coast Guard. The spill was initially reported on 29 December 1973. It was the result of a two-ship collision that took place about 18 km west of Cape San Martin, California, and about 83 km south of Monterey, California. The spill was composed of 60,000 liters (16,000 gallons) of bunker "C" oil. On 29 December the slick was reported to be 3 km long by 200 m wide. On 30 December the slick was reported to be about 250 wide and 18 km from land. Oil was continuing to drain from one of the vessels after it was anchored at 35°09'50" north latitude, 120°44'28" west longitude (see Figure 11).

Because the slick was well documented and seemed large enough to be seen by a satellite of ERTS-1 resolution, we investigated this event. ERTS-1 passed over the area on 30 December 1973 (frame #1525-18151) at 10 am local time when the sun was at an elevation of 24° above the horizon.

Both visual imagery and computer-compatible tapes were received for this site. This information appeared sufficient to assist in the data analysis even though no specific ground truth was available.

During the period from the initial collision to the ERTS-1 overpass, the wind was light to moderate, averaging about 0.5 m/sec on the first day, 3 m/sec on the second, and 2 m/sec on the third. This moderate wind could be sufficient to break up the slick into much smaller segments over the time period involved.

5.2 METHOD OF ANALYSIS - ELEVATED RADIANCE

As discussed in the theory section (Chapter 2), the reflectivity for oil floating on the surface of natural water varies slightly from that of the surrounding water. This assumes that the water is relatively clear and has little suspended or floating matter near or on the surface and that the surface is calm.

Using this small variation in reflectivity as a starting point, the three shorter-wavelength channels (MSS-4, 5, and 6) were used in the analysis. Not much information is contained in MSS-7 (0.8-1.1 μm) for work of this type.

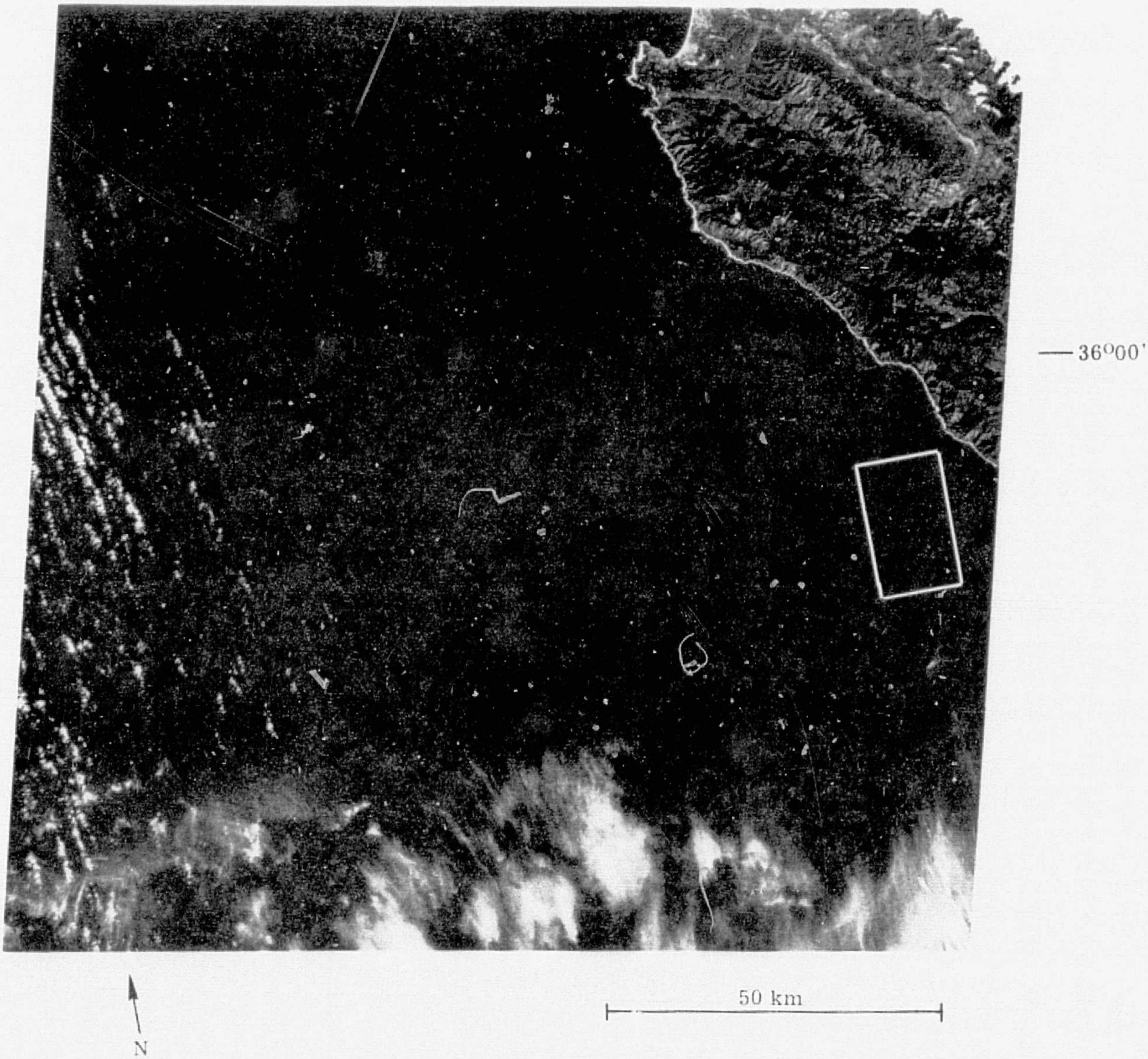

FIGURE 11. LOCATION OF CALIFORNIA-COASTAL SPILL. ERTS frame E-1525-18151, 30 December 1973, channel MSS-5, center frame coordinates: 35°58'N, 122°23'W.

The primary step in data analysis for this site was to eliminate the variability from one sensor (there are six sensors per channel) to another, as well as the variability of each individual sensor resulting from time or electronic drift. This was done by choosing non-land, non-nearshore areas and determining the average data value for each line. This value was still quantized to integer counts, as was the original data.

This line average was then subtracted from each data value (pixel) and 50 units added to this difference. (The 50 were chosen to give all channels the same average and a dynamic range of from 45 to 70 units, which meant the channels were then comparable and had the same relative magnitude and range.)

The result of this smoothing (by line) was then analyzed to determine the random fluctuations that could be expected from just the sensor noise. Table 6 shows the frequency of occurrence, percent of occurrence, and cumulative percent of all observed data values for the three channels that were analyzed. The above smoothing did correct each line and each channel to a condition such that each line average was 50 units, while also maintaining the original radiance per-count value for each channel.

The computer was then used to print maps (one for each of the three channels) that had a symbol indicating the count level for each pixel. These maps could then show pictorially the location of the anomalous values. Two final maps were made indicating those pixels whose radiance level was higher (the low values had no correlation by channel) than the average for two, and then three, channels at one time.

5.3 RESULTS OF ELEVATED-RADIANCE METHOD

The statistical data, as well as the five maps, were all analyzed. The results are discussed below.

For the three channels used (MSS-4, 5, and 6), the mode (count value with the maximum frequency of occurrence) in all cases is 50. The second highest value in occurrence is 49. There seems to be an even distribution both above and below 50 units. For MSS-4 and 5 the variations (noise) seem to be from 47-53 units, or 3 counts from the mean and mode. For MSS-6 the variation is from 48-52, or 2 counts from the mean and mode.

The three maps generated to show data variations for each channel separately indicated a random location of both high and low radiance values, as did the maps looking at two or three channels at the same time.

Although this method of analysis should have been sufficient to show at least the location of the spill, this was not accomplished. One possible explanation might be that the spill had already broken up to a great degree. Another might be that the satellite's resolution of 60 m by 80 m was not fine enough to see the small low contrast oil areas.

TABLE 6. FREQUENCY DISTRIBUTION OF DATA VALUES FOR CALIFORNIA-COASTAL SPILL

	Frequency of Occurrence			
Data Counts	MSS-4	MSS-5	MSS-6	MSS-7
41	-	-	-	21
43	-	-	-	125
44	-	-	-	11
47	4	45	-	-
48	583	585	612	-
49	3,774	4,247	6,834	3,134
50	14,226	12,493	10,187	14,120
51	948	2,125	1,942	2,411
52	287	335	266	25
53	45	31	35	4
54	15	12	10	2
55	3	11	7	-
56	2	4	4	-
57	7	8	1	-
58	1	2	2	-
59	-	2	1	-
61	3	-	-	-
64	-	1	-	-
65	1	-	-	-
73	-	-	-	7
75	-	-	-	33
76	-	-	-	4

Another possible explanation for random high-radiance spots involves sun glint off the water and wavelets. If the oil were broken up, the water may not have been under the calming effect that it would have been under if the spill had remained contiguous.

The last explanation is that the small differences in reflectivity between the oil and the water may not have been discernible with the noise level as high as it was.

6
OVERALL RESULTS

This chapter is devoted to summarizing the results of the work done during this study and discussed in this report.

6.1 SPECTRAL-SIGNATURE RESULTS

The method of generating spectral signatures, used for the Atlantic-Ocean spill, produced the following products: a recognition map, values of the mean and standard deviation of each ERTS-1 channel for each generated signature, inter-channel comparisons, and spectral displays of the signatures.

The recognition map distinguishes the different signatures in the spill. It shows a very bright center, a less bright edge, and an apparent darkening around the perimeter of the spill, along with other features such as clouds, haze, and possible break-up of the spill.

The listing of values of the mean and standard deviation for the four ERTS-1 spectral channels for each of the signatured materials shows a small variation from one signature to another and a very low signal level (in some cases, bordering on noise and background).

A comparison of the different spectral channels for the various signatures points out some other items. There is little probability of misclassification from one signature to another; in fact, the signatures (although very close in reflectance) appear fairly distinct. Also, some channels have good correlation with others (i.e., MSS-4, 5, and 6) and a variation in one of these channels produces a corresponding variation in another. Channel 7 shows little correlation with the others, however.

The spectral display of some of the signatures further helps identify what the materials might be, but it mainly points out graphically what their differences are.

A summary of the results of these various products shows the following:

(1) Analyzing ERTS-1 data by spectral-signature differentiation does separate some distinct materials on the surface of the water

(2) The analysis using the spectral-signature method appears to be more precise than the original data warrants

(3) The low data values, the large (spectrally wide) bandwidths, and the few number of spectral channels in the ERTS-1 scanner allow only very coarse identification of materials

(4) Since no ground truth was available, material identification, spill age, and characteristics were not determined

(5) The shape and spectral character of the anomaly is consistent with, but not confirmation of, the presence of a petroleum slick.

6.2 SPECTRAL-RATIO RESULTS

The spectral-ratio method produced tables of ratios of the four ERTS-1 spectral channels for the Oakland-Bay spill. The ratios covered 12 sites within the area.

The ratio technique shows overwhelmingly that the turbid condition of the water is the predominant characteristic affecting the water's reflective properties. Furthermore, the area investigated is also surrounded by highly reflecting land, which also tended to overshadow any oil effects.

6.3 ELEVATED-RADIANCE RESULTS

The method of elevated radiance was used to study the oil spill off the Southern-California coast. The products generated from this method were maps showing radiance variation of the area (one map for each spectral channel), a correlation map showing those areas with elevated radiance for more than one channel, and a frequency distribution of radiance (data counts) for each channel.

This method may be sufficient to point out suspected oil spills, but it is not as effective as the other methods in describing the characteristics or the material type in the area. Furthermore, it involves generating single-channel maps and, ultimately, a single map with many channels superimposed. This method may be of aid for initially detecting spills, but it is not sufficient to identify the material unless analysis of other types are also made.

6.4 RADIANCE SUMMATION RESULTS

The method of radiance summation was used for the Oakland-Bay spill. This method produced a table of values of the sum of radiance of two or more spectral channels for the 12 sites investigated.

The results of this method for the Oakland-Bay spill indicate that it is very difficult to show any of the sites contained oil on the water surface, although the ground truth indicated some did. The turbid condition of the water, as well as the immediate adjacency of land, overshadowed the effects of any oil that may have been present.

7
EVALUATION OF ERTS-1 AS AN OIL-POLLUTION DETECTOR AND MONITOR

This chapter evaluates ERTS-1 as an oil-pollution detector and monitor. It investigates the type of detectors used, the wavelength channels, the resolution, the frequency of overpass, and the information-retrieval time.

7.1 SENSORS AND THEIR SENSITIVITY

The type of radiation-detecting equipment used on the ERTS-1 multispectral scanner took into consideration the speed of the satellite with respect to the ground, the length of time a particular area of earth was visible, and the expected range of radiances that would be seen through the optics.

Because the satellite was constantly in motion with respect to the earth's surface, six sequential sensors were used to anticipate this motion. Also, since the time allowable for the satellite to image on a particular area was relatively short, the sensors had to have a short time constant. As a result of this sequential operation of the sensors, the calibration of a particular sensor within the array was subject to change relative to the other five. This resulted in "striping," in which a particular sensor indicated a change in radiance, either higher or lower than the rest of the array. While looking at small areas, it is sometimes difficult to determine if this change in radiance is due to the ground changing actual reflectance to the sensor changing calibration. To eliminate this local change in calibration, some "smoothing" of the data is used which may cover true changes in radiance. Furthermore, since the sensors require a very short time to see and accept radiation from an area of the earth's surface, the ultra sensitivity required for oil-detection work was not possible.

The dynamic range of the detector array produced a second difficulty. Since the areas being investigated in this report were all concerned with water or oil and water, the detector array was subjected to very low radiance levels. As a result, there is a very small range of detected values. The ERTS-1 system had a requirement to cover both water (low reflectance) and snow (high). And the result was a very small change in output when the satellite was moving across water areas. A greater sensitivity would have enabled the oil analysis to take into account small radiance changes (as well as understand systematic background changes caused by electronic noise) and finally to better separate water from oil.

7.2 SPECTRAL CHANNELS AND THEIR BANDWIDTHS

In order to determine the presence or status of an oil spill on the surface of water, it is necessary to be able to separate the naturally occurring effects of the water from those of the oil. The spectral channels used on the ERTS-1 satellite were relatively inefficient in accomplishing this end.

The MSS-4 channel (0.5-0.6 micrometers) and the MSS-5 channel (0.6-0.7 micrometers) were of such a bandwidth as to suppress good discrimination of changes in chlorophyll and suspended sediment in the water, which could hide the effects of oil. These are the only ERTS-1 channels that can significantly penetrate the water's surface. A greater number of channels within the spectral region from 0.4-0.7 micrometers would have allowed more discrimination as to the events naturally occurring in the water and their changes, as well as aiding in the analysis of the spills as to the type of material and the characteristics involved.

Another difficulty in using ERTS-1 as an oil detector was the lack of thermal-infrared data. The maximum wavelength seen by the satellite was 0.8-1.1 micrometers (MSS-7). In order to evaluate changes in thermal emissivity or temperature which may be the result of a foreign material on the surface of the water, it is necessary to use thermal data. This lack in the ERTS-1 scanning system seriously hampered this analysis.

7.3 RESOLUTION

Most oil spills which are damaging to the environment cover a large area on the water surface. The resolution element on the ERTS-1 satellite (60 m by 80 m) was in most cases sufficient to identify this area. A better resolution is often desirable to help pinpoint a specific source. But in the case of oil-pollution detection or monitoring this is quite often not necessary (except in the case of a spill break-up), and the resolution allowed by ERTS-1 appears sufficient.

7.4 OVERPASS FREQUENCY

The ERTS-1 satellite observes each portion of the earth once every 18 days. This frequency is sufficient for long-term changes in the events occurring on the earth's surface. However, detection of an oil spill (especially a new one) requires very frequent observations of suspected spillage areas. The possibility of a cloud cover during overpass or a spill occurring within the 18-day cycle is exceptionally high. To detect new spills requires very frequent observations, at least daily, and to monitor the progress of a spill (for clean-up or motion) requires observations every few hours. Since these observations are not supplied by ERTS-1, very few oil spills can be seen, found, and investigated with this satellite. The Appendix provides a list of major spills that were coincident with ERTS-1 overflights.

7.5 INFORMATION-RETRIEVAL TIME

The elapsed time that occurred between the time that ERTS-1 passed over an area and the time the investigator received information to process the data for that area was usually weeks or even months. Although ERTS-1 is only an experimental satellite, its usefulness for effecting reasonable detection and any monitoring is considerably decreased by this long time

delay. It is estimated that a minimum time required for receiving satellite information in order to be effective as a detector or status monitor for oil spills is about four hours [12]. The ERTS-1 program did not allow for such a short time and, therefore, was not effective for detection or monitoring—it was usable, however, for a feasibility study.

8
CONCLUSIONS AND RECOMMENDATIONS

This chapter discusses both the usability of ERTS-1 as an oil-pollution detector and monitor and the usefulness of any satellite for such a purpose. It also presents recommendations concerning the minimum acceptable requirements for such a system.

8.1 USABILITY OF ERTS-1 AS AN OIL-POLLUTION DETECTOR AND MONITOR

This report has discussed the use of the ERTS-1 multispectral-scanner system for detecting and monitoring oil spills on the water. It has gone into some of the theory of oil-pollution monitoring by satellite and described the procedures and results of the evaluation of three different spills. In all three cases, it was not possible to make an affirmative statement that there was oil present, in spite of the fact that two of the three spills had ground confirmation of oil.

Many factors were involved in the lack of such an affirmative statement. One was the non-consistent behavior of the sensor array, which required a mathematical smoothing of the data which, in turn, could have overriden the effects of the oil. Another factor was the extremely broad wavelength channels, which made it difficult to accurately determine the state of the water beneath the suspected oil and thereby separate the water in its natural condition from any effects of the oil. The few number of channels magnified this effect, as well as preventing evaluation of thermal emissivity. Another factor in limiting the use of this satellite was the limited overpass frequency over each area of the earth. This resulted in observations no more frequent than once every 18 days—in some cases much further apart as a result of clouds, haze, and other causes. Another factor preventing good satellite reconnaissance of oil spills was the long information-retrieval time. The delay of weeks prevented any positive action from being carried out regarding the movement or clean-up of the spill. Finally, there was the difficulty in looking at nearshore water because of backscattered radiation from the land, which tended to overshadow the water and any effects of oil.

It is difficult, therefore, to say that ERTS-1 was or is useful as a detector or monitor of oil spills.

8.2 USE OF ANY SATELLITE AS A DETECTOR OR MONITOR OF OIL POLLUTION

Although the above conclusions appear pessimistic, the results of this study do in many ways indicate the feasibility of a satellite monitor and detector for oil spills. The advantages of such a system would be that it could look from an elevated position without hinderance (except for the atmosphere). The system could operate day and night and even could have built-in alarms to warn us if a spill occurs.

To accomplish such a goal, however, it is imperative that the satellite often observe the areas most likely to be affected. This frequency should not be longer than 24 hours, and it might be less in more susceptible locations. To further enhance the capabilities of such a system, the number of spectral channels would have to be increased to allow for better discrimination of effects due to oil from those of suspended organic and inorganic matter [7, 8, 9, 10, 11, 12]. The bandwidths should be no wider than 0.05-0.07 micrometers in the visible region of the spectrum. An example of such an array of channels is 0.47-0.52, 0.53-0.57, 0.56-0.60, and 0.65-0.69 micrometers [12]. Furthermore, the minimum detectable change in reflectivity (including the optics and electronics) should be no greater than 1%. Thusly, the small changes in the surface of the water resulting from the presence of oil could be seen and separated from natural changes in the water quality. Other band requirements would include a thermal capability to evaluate the change in thermal emissivity of the surface caused by the presence of a foreign material. This system should have a minimum detectable difference of $1^{o}C$ or less [2, 3, 5, 12]. This thermal capability would allow observation during night hours and aid in identification during the daylight.

Another necessity to make the satellite a feasible oil monitor and detector is a quick information and data-retrieval system. A time lag of greater than four hours is not acceptable. This high-speed retrieval will allow for quick analysis, which, in turn, will result in fast corrective measures taken on the ground.

Finally, in order to allow for a longer time for observation, the satellite should view the area long enough to allow the build-up of cumulative radiance which will amplify the very small reflected signals from the oil and the water.

These requirements appear to indicate that a stationary satellite such as the proposed Synchronous Earth Observatory Satellite [12] should be used. Such a satellite will meet all or most of these requirements and, thereby, would be most useful to detect and monitor oil spilled on the water in time to prevent serious environmental damage and also to assist in clean-up operations.

APPENDIX

Coincidence of Major Spills and ERTS Overflights

Location	Oil Type	Quantity (gal.)	Report Date	Clean Date	ERTS Date	Comments
Salem, Massachusetts	#2 and #5 Fuel Oil	29,500	2 Oct. 1972	After 4 Oct. 1972	8 Oct. 1972	Good Data Too Late
Barataria Bay, Louisiana	Crude	336,000	9 Oct. 1972	Dissipated before 17 Oct. 1972	18/19 Oct. 1972	Overcast
San Antonio, Texas	Diesel Fuel	678,000	11 Oct. 1972	≈17-18 Oct. 1972	24 Oct. 1972	Too Late
San Juan City, New Mexico	Crude	100,000	12 Oct. 1972	≈1 Nov. 1972	16/17 Oct. 1972	Overcast
Lake Barre, Louisiana	Crude	29,400	22 Nov. 1972	≈24 Nov. 1972	23/24 Nov. 1972	Overcast
Albemarle Sound, North Carolina	Bunker C	1,000	28 Nov. 1972	29 Nov. 1972	3 Dec. 1972	Good Data Too Late
Gulf Coast Penzoil Rig J, Storm II	Gasoline and Oil (burning)	?	4 Dec. 1972	6 Dec. 1972	11 Dec. 1972	Overcast Too Late
Timabalier Bay, Louisiana (well blowout)	Gasoline, Light	(minor ?)	6 Dec. 1972	?	12 Dec. 1972	Overcast
Jennings, Louisiana (Bayou Nezpique)	Crude	156,000	14 Dec. 1972	?	12/13 Dec. 1972	Too Early
Alameda, California (Naval Air Station)	10% Diesel Fuel 20% Solvent 70% 20/40 Lube	> 1,400	22 Dec. 1972	23 Dec. 1972	17 Dec. 1972	Too Early
Fenwick, Connecticut (Long Island Sound)	#6 Fuel Oil	12,000	26 Dec. 1972	30 Dec. 1972	7 Jan. 1973	Too Late
Gulf Coast, Louisiana (Pltfm A West Delta 79, Signal Oil Co.)	Crude	400,000	10 Jan. 1973	11. Jan. 1973 (dissipated)	15/16 Jan. 1973	Too Late
Oakland, California	Waste Oil	≈120,000	19 Jan. 1973	Contained 24 Jan. 1973 Completed 4 Feb. 1973	22/23 Jan. 1973	Tapes Processed

APPENDIX (cont.)

Location	Oil Type	Quantity (gal.)	Report Date	Clean Date	ERTS Date	Comments
Vicksburg, Mississippi	#2 Fuel Oil	189,000	31 Jan. 1973	3 Feb. 1973 (dissipated)	4 Feb. 1973	Too Late
Baton Rouge, Louisiana	Crude	500,000	1 Mar. 1973	Before 13 Mar. 1973	12 Mar. 1973	Too Late
Bellingham, Washington	?	est. 1,000 (7 sq. mi. slick)	2 Mar. 1973	?	3 Mar. 1973	Overcast
Cold Bay, Alaska	Diesel Fuel and Gasoline	235,000	9 Mar. 1973 (start 8 Mar.)	18 Mar. 1973	14/15 Mar. 1973	Overcast
Houston, Texas	Oil and Diesel	420,000	12 Mar. 1973 (start 9 Mar.)	19 Mar. 1973	15 Mar. 1973	Overcast
LaParguera, Puerto Rico	Crude	1,600,000	19 Mar. 1973	After 5 Apr. 1973	29 Mar. 1973	No Data Taken
Baton Rouge, Louisiana	Slop Oil	40,000	28 Mar. 1973	After 29 Mar. 1973	30 Mar. 1973	Overcast
Providence, Rhode Island	#6 Fuel Oil	50,000	12 Apr. 1973	Before 20 Apr. 1973	24 Apr. 1973	Too Late
Norfolk, Virginia	Navy Distillate	30,000	27 Apr. 1973	?	26 Apr. 1973	Too Early
Grand Isle, Louisiana	Crude	240,000	11 May 1973	15 May 1973	22 May 1973	Too Late
Atchafalaya River Morgan City, Louisiana	Crude	63,000	31 May 1973	?	10 Jun. 1973	Too Late
Monangahela River Duquesne, Pennsylvania	#6 Fuel Oil	40,000	1 Jun. 1973	14 Jun. 1973	5 Jun. 1973	Images Reviewed
New York Harbor (M/V Exxon Brussels)	Crude	<80,000	2 Jun. 1973	Before 21 Jun. 1973	1/19 Jun. 1973	Too Early and Too Late
Santa Barbara Channel (Coal Oil Point)	Crude	? Seeping	5 Jun. 1973	?	13 Jun. 1973	Images Reviewed
Oakland, California	Bunker C	5,000	5 Jun. 1973	6 Jun. 1973	15/16 Jun. 1973	Too Late

APPENDIX (cont.)

Location	Oil Type	Quantity (gal.)	Report Date	Clean Date	ERTS Date	Comments
Atlantic Ocean (37°30'N 74°30'E)	?	?	?	?	6 Jul. 1973	Tapes Processed
Rouge River, Detroit, Michigan	#4 Fuel Oil and Kerosene	20,000	28 Jun. 1973	9 Jul. 1973	26 Jun. 1973 14 Jul. 1973	Too Early and Too Late
Savannah River Savannah, Georgia	Tallow	29,800	6 Jul. 1973	10 Jul. 1973	9 Jul. 1973	Too Late
Northport, Long Island, New York	#6 Fuel Oil	5,000	9 Jul. 1973	10 Jul. 1973	6/24 Jul. 1973	Too Early
Mississippi River Mile 88	Crude	210,000	11 Jul. 1973	12 Jul. 1973	28 Jun. 1973 16 Jul. 1973	Too Early and Too Late
Tennessee River Mile 446	#2 Diesel Fuel	15,000	18 Jul. 1973	19 Jul. 1973	13 Jul. 1973	Too Early
Lake Michigan Chicago, Illinois	?	"major"	18 Jul. 1973	18 Jul. 1973	16 Jul. 1973	Too Early
Ohio River Mile 894	Gasoline	84,000	7 Aug. 1973	7 Aug. 1973	1/19 Aug. 1973	Too Early and Too Late
Oakland, California Outer Harbor	Diesel Fuel	3,500	6 Sep. 1973	7 Sep. 1973	14 Sep. 1973	Too Late
Portland, Oregon	Bunker	40-75,000	6 Sep. 1973	90% by 12 Sep. 1973	16 Sep. 1973	Too Late
Houston, Texas	Marine Crude	40-160,000	9 Sep. 1973	11 Sep. 1973	15 Sep. 1973	Too Late
Mississippi River 85 Mi. AHOP	Crude	1,500	9 Sep. 1973	14 Sep. 1973	8 Sep. 1973	Too Late
Norfolk, Virginia	-	1,500	14 Sep. 1973	-	16 Sep. 1973	Overcast
Vancouver, British Columbia	-	100,000	25 Sep. 1973	After 27 Sep. 1973	4 Oct. 1973	Too Late
San Francisco Bay	Fuel Oil	2,000	27 Sep. 1973	2 Oct. 1973	2 Oct. 1973	Too Late

Location	Oil Type	Quantity (gal.)	Report Date	Clean Date	ERTS Date	Comments
Columbus, Georgia Chattahoochee River	Gasoline	8,100	5 Oct. 1973	-	10 Oct. 1973	Too Late
Gulf of Mexico (28°20'N 93°29'W)	Diesel Fuel	-	12 Oct. 1973	-	15 Oct. 1973	Overcast
Enid, Oklahoma Cimarron River	Crude	250,000	15 Oct. 1973	After 23 Oct. 1973	20 Oct. 1973	Too Late
Bronx, New York East River	-	80,000	16 Oct. 1973	19 Oct. 1973	23 Oct. 1973	Too Late
Albany, New York Hudson River	#6 Fuel Oil	20,000	19 Oct. 1973	23 Oct. 1973	23 Oct. 1973	Too Late Overcast
Vancouver, British Columbia	Bunker C	3,000	26 Oct. 1973	28 Oct. 1973	22 Oct. 1973	Too Early
Padilla Bay, Washington	Diesel Fuel	-	12 Nov. 1973	-	9/10 Nov. 1973	Too Early
Pittsburgh, Pennsylvania	#2 Fuel Oil	5,000	12 Nov. 1973	14 Nov. 1973	14 Nov. 1973	No Data
Atlantic Coast (35°20'N 75°05'W)	Diesel Fuel	6,000	12 Nov. 1973	15 Nov. 1973	9 Nov. 1973	Too Early
Cincinnatti, Ohio Ohio River	-	130,000	1 Dec. 1973	7 Dec. 1973	5 Dec. 1973	Overcast
Seattle, Washington	JP-4	15,000	3 Dec. 1973	7 Dec. 1973	15 Dec. 1973	Too Late
St. Francisville, Louisiana Mississippi River	Fuel Oil	16,000	5 Dec. 1973	-	6/7 Dec. 1973	Data Good, Site Small
Elk River, Minnesota Mississippi River	#4 Fuel Oil	40,000	11 Dec. 1973	-	12 Dec. 1973	No Data
Cape Cod Canal	Fuel Oil	300,000	21 Dec. 1973	-	31 Dec. 1973	Too Late
Sabine, Texas	Gulf Crude	63,000	22 Dec. 1973	25 Dec. 1973	28 Dec. 1973	Too Late
Houston, Texas	Light Crude	84,000	23 Dec. 1973	After 25 Dec. 1973	28 Dec. 1973	Too Late

APPENDIX (cont.)

Location	Oil Type	Quantity (gal.)	Report Date	Clean Date	ERTS Date	Comments
Philadelphia, Pennsylvania Delaware River	Nigerian Crude	4-126,000	26 Dec. 1973	28 Dec. 1973	4 Jan. 1974	Too Late
Mississippi River Mile 20	Gasoline	5,000	28 Dec. 1973	-	25/26 Dec. 1973	Too Early
Pacific Ocean South of Monterey, California	Bunker C	16,000	29 Dec. 1973	12 Jan. 1574	30 Dec. 1973	Tapes Processed
Trenton, New Jersey Delaware River	#2 Fuel Oil	20,000	3 Jan. 1974	14 Jan. 1974	3 Jan. 1974	Too Early
Estherville, Kansas Desmoines River	#1 Fuel Oil	2,000	15 Jan. 1974	16 Jan. 1974	18 Jan. 1974	Too Late
New Orleans Harbor	-	630,000	15 Jan. 1974	24 Jan. 1974	20 Jan. 1974	Too Late
Krotz Springs, Louisiana Atchafalaya River	Crude	546,000	16 Jan. 1974	17 Jan. 1974	30/31 Jan. 1974	Too Late
Mississippi River 1.5 mil AHOP	Gasoline #2 Fuel Oil Jet Fuel	2,800,000 2,600,000 672,000	18 Jan. 1974	-	29 Jan. 1974	Too Late
Chicago, Illinois, San. and Ship Canal	#4 Fuel Oil	2,000	22 Jan. 1974	24 Jan. 1974	30/31 Jan. 1974	Too Late
Ft. Walton, Destin, Florida	Bunker C	1,000	30 Jan. 1974	13 Jan. 1974	28 Jan. 1974	Too Early
Northville, New York Long Island Sound	-	10-20,000	31 Jan. 1974	1 Feb. 1974	6 Feb. 1974	Too Late
Bear Mt. Park, Hudson River, New York	Fuel Oil	20,000	11 Feb. 1974	25 Feb. 1974	24 Feb. 1974	Too Late
Paulsburo, New Jersey	Bunker	285,000	19 Feb. 1974	25 Feb. 1974	26 Feb. 1974	Too Late
Norwich, Connecticut	#2 Fuel Oil	42,000	21 Feb. 1974	After 22 Feb. 1974	24/25 Feb. 1974	Too Late
Milwaukee, Wisconsin Menomenee River	#2 Diesel Fuel	3,000	21 Feb. 1974	After 25 Feb. 1974	18 Feb. 1974	Too Early

REFERENCES

1. Robert Horvath, W. L. Morgan, and R. Spellicy, Measurements Program for Oil-Slick Characteristics, Final Report for Contract DOT-CG-92580-A, Willow Run Laboratories, Ann Arbor, Michigan, 1970.
2. Robert Horvath, Interpretation Manual for the Airborne Remote Sensor System, Report for Contract DOT-CG-33568-A, Environmental Research Institute of Michigan, Ann Arbor, Michigan, 1974.
3. Robert Horvath, W. L. Morgan, and S. R. Stewart, Optical Remote Sensing of Oil Slicks: Signature Analysis and Systems Evaluation, Final Report for Contract DOT-CG-92580-A, Willow Run Laboratories, Ann Arbor, Michigan, 1971.
4. J. Millard and J. Arversen, Results of Airborne Measurements to Detect Oil Spills by Reflected Sunlight, in Remote Sensing of Southern California Oil Pollution Experiment, 1971 Pollution Control Branch, Applied Technical Division, United States Coast Guard, Washington, D. C., 1971, pp. 38-62.
5. Robert Horvath and S. R. Stewart, Analysis of Multispectral Data from the California Oil Experiment of October 1971, in Remote Sensing of Southern California Oil Pollution Experiment, 1971 Pollution Control Branch, Applied Technical Division, United States Coast Guard, Washington, D. C., 1971, pp. 91-106.
6. Harry G. Stumpf and Alan E. Strong, ERTS-1 Views an Oil Slick?, in Remote Sensing of the Environment, Vol. 3, 1974, pp. 87-90.
7. C. T. Wezernak and F. C. Polcyn, Technological Assessment of Remote Sensing Systems for Water Pollution Control, Report No. 035790-4-L, Willow Run Laboratories, Ann Arbor, Michigan, 1971.
8. C. T. Wezernak and F. C. Polcyn, Technological Assessment of Remote Sensing Systems for Water Pollution Control, Report No. 10011-3-F, Willow Run Laboratories, Ann Arbor, Michigan, 1972.
9. Harold L. Yarger, James R. McCauley, Gerard W. James, Larry M. Magnesson, and G. Richard Marzolf, Quantitative Water Quality With ERTS-1, in Third Earth Resources Technology Satellite-1 Symposium, NASA SP-351, Scientific and Technical Information Office, NASA, Washington, D. C., 1974, pp. 1637-1651.
10. R. C. Ramesey, Study of the Remote Measurement of Ocean Color, Report No. TRW-NASA-1658, TRW Corporation, Los Angeles, California, 1968.
11. F. C. Polcyn and R. A. Rollin, Remote Sensing Techniques for the Location and Measurement of Shallow-Water Features, Report No. 8973-10-F, Willow Run Laboratories, Ann Arbor, Michigan, 1969.
12. Gary C. Goldman, et al., Investigation of Transient Earth Resources Phenomena: Continuation Study, Report No. 107400-2-F, Environmental Research Institute of Michigan, Ann Arbor, Michigan, 1974.